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An investigation into the materials used for the encapsulation of turbine blades

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Award date:
1978

Awarding institution:
Coventry University

LANCHESTER POLYTECHNIC

THESIS

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AN INVESTIGATION INTO THE MATERIALS USED FOR THE ENCAPSULATION OF TURBINE BLADES.

SUBMITTED AS PARTIAL REQUIREMENTS FOR
DEGREE OF MSc in ENGINEERING MANUFACTURE

YEAR: 1978

SUBMISSION DATE:
1st September.

ACKNOWLEDGMENTS

The author would like to thank the following for their assistance in the preparation of this thesis:

B. E. Tarling for his help with the experimental work.

Rolls Royce Ltd, Glasgow, for providing a quantity of Frycap 7 alloy.

Rolls Royce Ltd, Derby, for permission to reproduce the photograph of the jet engine.

Mining and Chemical Products Ltd, for supplying a quantity of Cerrotru and Cerrocast, and for carrying out the metallurgical analysis of the alloys.

W. Brady for his guidance and advice.

P. B. Caulfield for his assistance.

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SUMMARY

Turbine blades account for the major part of the cost of the aero-gas turbine engine. Many thousands of blades are used in each engine. All are made of sophisticated materials machined to very fine limits.

A high technology industry manufacturing turbine blades has grown up in the last 30 years. A relatively new technique of blade manufacture has been developed during the past 15 years. This is blade encapsulation and is used in conjunction with precision forging and precision casting of blades. Encapsulation involves casting a block of low melting point alloy around the precision formed blade, such that the aerofoil is in the correct position relative to the three datum faces of the encapsulation block. The blade is then machined with resultant higher production rates, less scrap and the use of a lower grade of labour. Automation is possible with a blade production line using encapsulating techniques.

A survey of current blade encapsulation practices was undertaken on a world wide basis and the results indicate widely differing methods.

Research has been undertaken into three commonly used encapsulating materials. The effects of varying the parameters of the encapsulating process on the physical properties of the encapsulation material, were investigated. The parameters varied were die temperature, alloy pouring temperature and elapsed time after casting. The physical properties under test were hardness, dimensional stability and the blade holding capability.

The results of the experiments were statistically analysed using factorial analysis. This is a powerful technique which enabled the significance of the main effects and the interaction between the main effects to be established. There were nine 3 x 3 factorial experiments in the research programme. Not all the experiments gave definite results. The blade holding force tests gave inconclusive results.

The research programme enabled firm conclusions to be drawn regarding encapsulating materials and effects of changing the parameters of the process. It is intended that these conclusions will assist blade manufacturers in optimising their blade encapsulating process.

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1. INTRODUCTION

1.1 The Gas Turbine Aero Jet Engine

The development of the aero jet engine has been one of the greatest technical achievements of the present century. The progress has been rapid, and consequently air travel today is cheap, safe and confortable. It is cheaper to fly from London to New York than to drive a car between London and Aberdeen.

The development of the gas turbine engine has been so swift, largely because of the defence requirement for faster and more sophisticated military aircraft by the western countries. Britain and USA have played the biggest role in the work on aero engines and today Rolls Royce Limited, of U.K., Pratt and Whitney and General Electric of USA are the only three companies with the capability of designing and building jet engines suitable for powering large 300-400 seat wide-bodied jets.

The gas turbine engine is an excellent example of a high technology product combined with series production. Many new manufacturing processes were developed expressly to produce the engine parts, and these processes have been used successfully in other industries. For example the carbon fibre material which combines light weight with high longitudinal strength was developed by Rolls Royce for the fan blade of the RB 211 engine which powers the Tristar aircraft. This material now has many industrial applications. Problems were encountered initially with this material because, as so often happens in high technology industries, production requirements overlapped research and development.

The gas turbine aero engine works on a simple principle.

1.2 Principle of the Gas Turbine Jet Engine (Reference 1 and 2)

The gas turbine comprises four basic parts; the compressor, the combustion chamber, the hot gas turbine, and the exhaust nozzle.

The engine admits air at atmospheric pressure and this is progressively compressed as it passes through the compressor turbine. The air is also heated as it is compressed. (Figure 1)

In the combustion chamber the fuel, usually paraffin, mixes with the hot compressed air and is burnt. The hot gases expand, resulting in high velocity and pressure. They pass through the hot gas turbine, expanding slightly as energy is expended in driving the turbine. The turbine drives the compressor.

Finally the hot gases pass through the exhaust nozzle. The reaction to the mass of gas leaving the nozzle propels the aircraft forward.

Temperatures in the engine are high. Combustion chamber temperature reaches almost $1000^{o}C$ whilst the hot gas turbine temperature is approximately $800^{o}C$. Compressor temperature is lower and rises as the air is compressed to a maximum of $400^{o}C$.

The compressor turbine and hot gas turbine have several stages of stator and rotor blades and these have to withstand arduous operating conditions. The blades in the hot gas turbine are usually air cooled.

Footnote: For convenience, the term turbine blade will be used to denote both compressor blades and hot gas turbine blades unless there is an important reason to define them specifically.

Figure 1: Rolls Royce gas turbine engine

This photograph has been removed for copyright reasons.

1.3 Turbine Blades

The blades are precision components upon whose design and manufacture the efficiency of the engine depends. Reliability is vital when an aeroplane is carrying 400 passengers at 35,000 feet at a speed of 650 mph. A blade failure could prove catastrophic.

The manufacture of gas turbine blades is a large industry with a turnover in the UK of tens of millions of pounds per annum. Both aero engine manufacturers and specialist blade manufacturers have a part to play, and each depends upon the other. Rolls Royce Ltd, is dominant in Europe, whilst Pratt and Whitney Inc and General Electric Inc dominate the United States. All manufacturers have their own production techniques and a survey has been made of current methods used, particularly those involving blade encapsulation (Appendix A).

Turbine blades are made in many ways:

a) from solid bar

b) from forgings and machined all over

c) from precision forgings

d) from castings and machined all over

e) from precision castings

The aerofoil is very difficult to generate by machinery, and the most economical way to produce blades in quantity is by precision forging or precision casting.

When either precision castings or precision forgings are used, the aerofoil section needs only polishing for it to be in the final finished state. This leaves the leading edge, trailing edge, tip and root (fir tree section) to be machined, using the aerofoil as the datum.

Several factors combine to make these machining operations difficult;

a) the blade material: high nickel alloy steels are used for the turbine blades whilst titanium is used for the compressor blades. Both materials are difficult to machine.

b) the aerofoil section is usually thin and would distort easily if gripped to support the blade during the machining of the root. The thin section of the aerofoil would also be unable to withstand the vibration arising when machining the root.

c) the tight machining tolerances necessary for high thermal efficiency of the engine are extremely difficult to maintain.

The ideal fixture for locating a blade precision forging or casting would:

a) be easy to load using unskilled labour.

b) support all the aerofoil section and enable large cuts to be taken when machining the root.

c) dampen machining vibrations.

d) present three simple datum faces for use on each of the machine tools in the machining sequence.

Conventional pin locators acting also as clamps do not satisfy many of these requirements but a process developed over the past 12 years does. This process is "Turbine Blade Encapsulation".

2 TURBINE BLADE ENCAPSULATION

2.1 The Encapsulation Process

In this process, the precision forging or precision casting is located by means of datum pins on three points on the aerofoil sections, two pins in the leading edge and one pin under the root. (Figure 3).

These pins have spring-loaded support pins on the opposite points of the blade, so that the blade is located and held in a correct position in space. The blade is held thus in a rectangular cavity and into this cavity is cast an encapsulating material.

When solid, the blade is encapsulated in a rectangular prism which has three datum faces, enabling the root and tip to be partly or fully machined by broaching, milling, turning, grinding, ECM or EDM depending on the blade material and the treatment required.

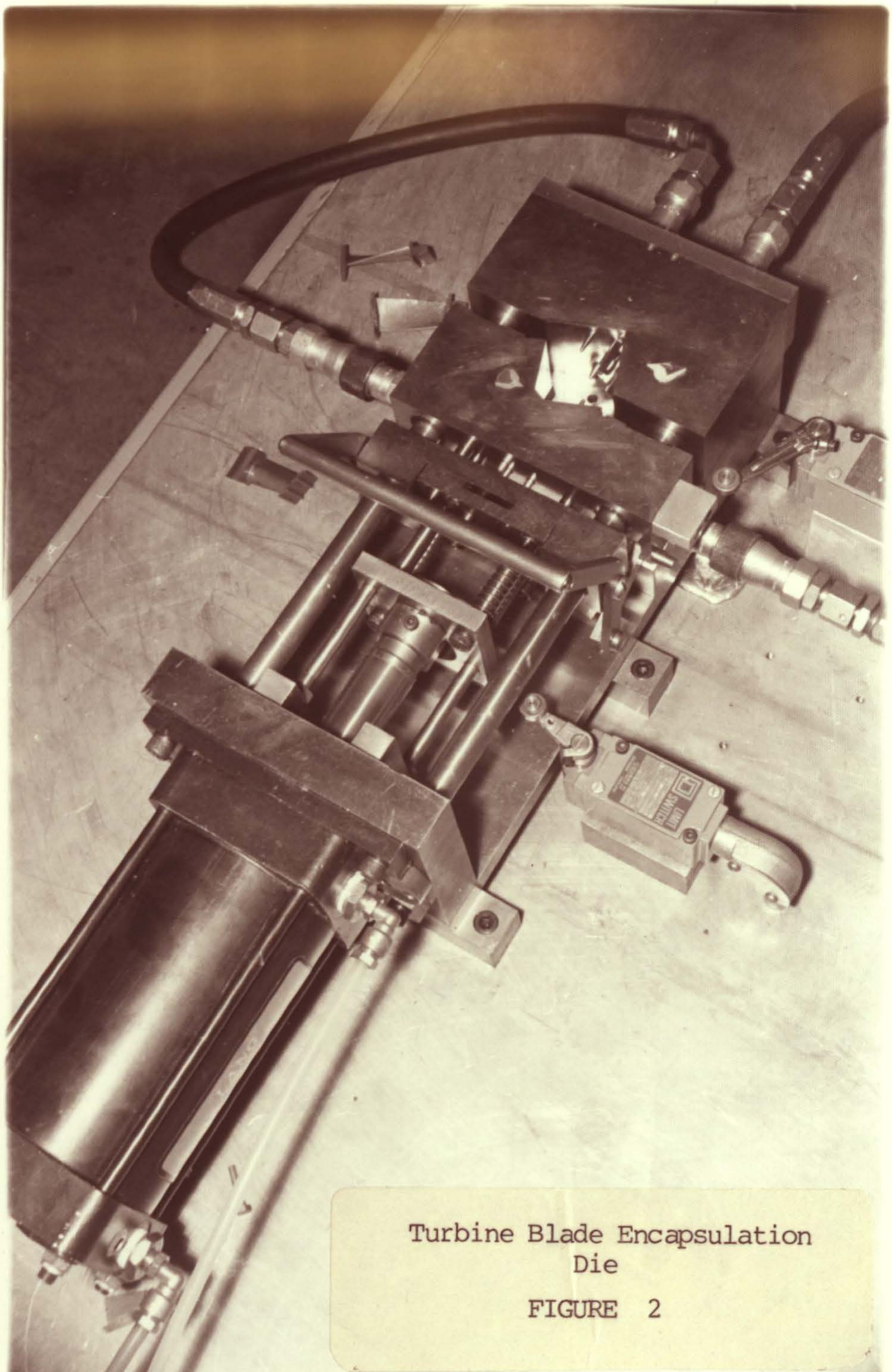
The blade is removed from the encapsulation when the machining has been completed.

2.2 The Encapsulation Die

There are two methods of introducing the encapsulating material onto the die. These are pressure feed and gravity feed.

Pressure feed is used when very large quantities of each type of blade are to be produced. Molten metal encapsulates the blade at a pressure of $20Kg/Cm^2$. The encapsulating machines and dies are expensive, and few companies have the requirement for this type of production. The alloy used is lead based and usually of a similar composition to type metal.

The most commonly used system is when the alloy is introduced



Turbine Blade Encapsulation
Die

FIGURE 2

into the die by gravity feed. The die cavity can be shaped according to the requirement of the machining operation but is usually a rectangular prism, (Figure 4)

All the datum pins are, if possible, located in the datum die half. The datum pins are usually 5 mm in diameter and have rounded ends, (Figure 5).

Occasionally the location point underneath the platform of the blade will be on an undercut face and a retractable datum pin may be necessary. Some accuracy may be lost when the pin is moveable.

The moving die half runs on two guide bars and is opened and closed by an air or hydraulic cylinder. After encapsulation the moving die half is opened. taking the encapsulation with it, and so drawing it off the datum pins. The final part of the stroke of the opening cylinder draws the spring-loaded pins out of the encapsulation leaving it free to be removed, either manually or mechanically.

The two die halves are temperature controlled by circulating water. At the start of the shift, hot water is circulated to bring the die up to a temperature of approximately 35°C. When the die is hotter than 45°C, an air to water heat exchanger operates to cool the die. At die temperatures between 35°C and 45°C, water is circulated with neither the heaters nor the heat exchanger operating. This assumes that the optimum die temperature is 40°C, and part of the experimental work of this thesis is to determine the effect of variation in die temperature on the physical properties of the encapsulation.

Cirrus Equipment Limited have developed encapsulation dies with pins electrically insulated where they pass through the die

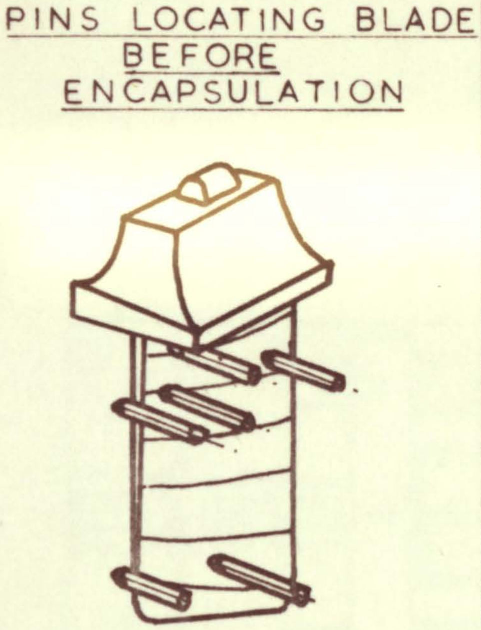


FIGURE 3

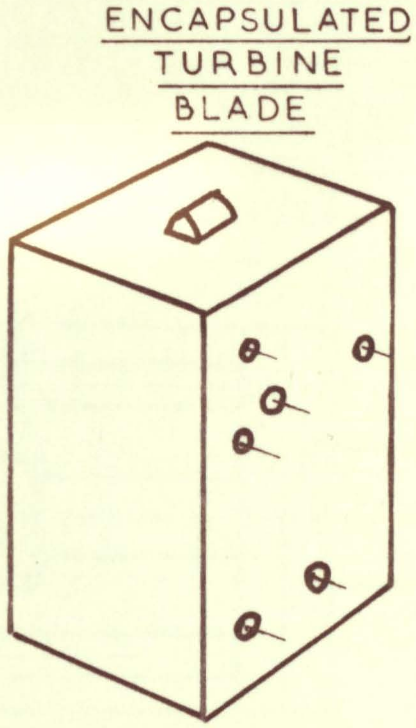


FIGURE 4

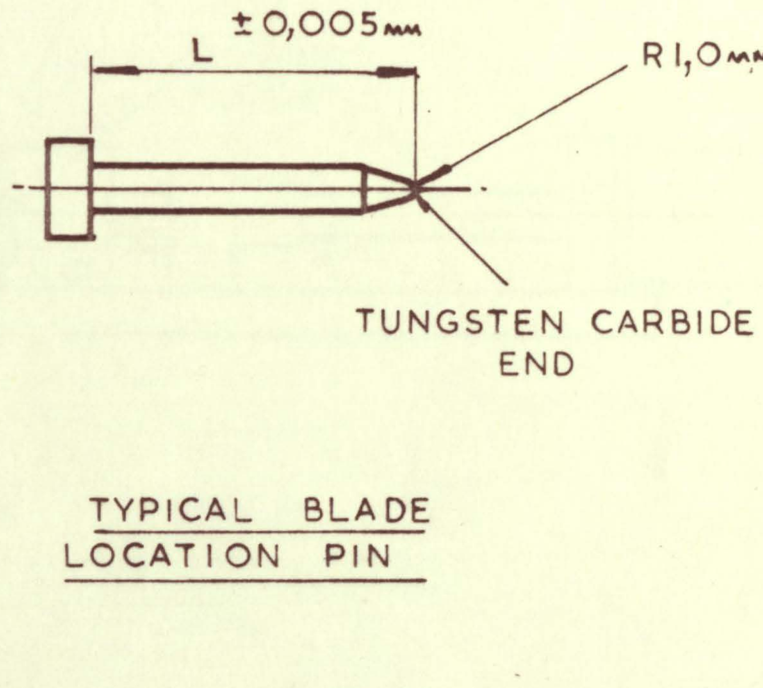
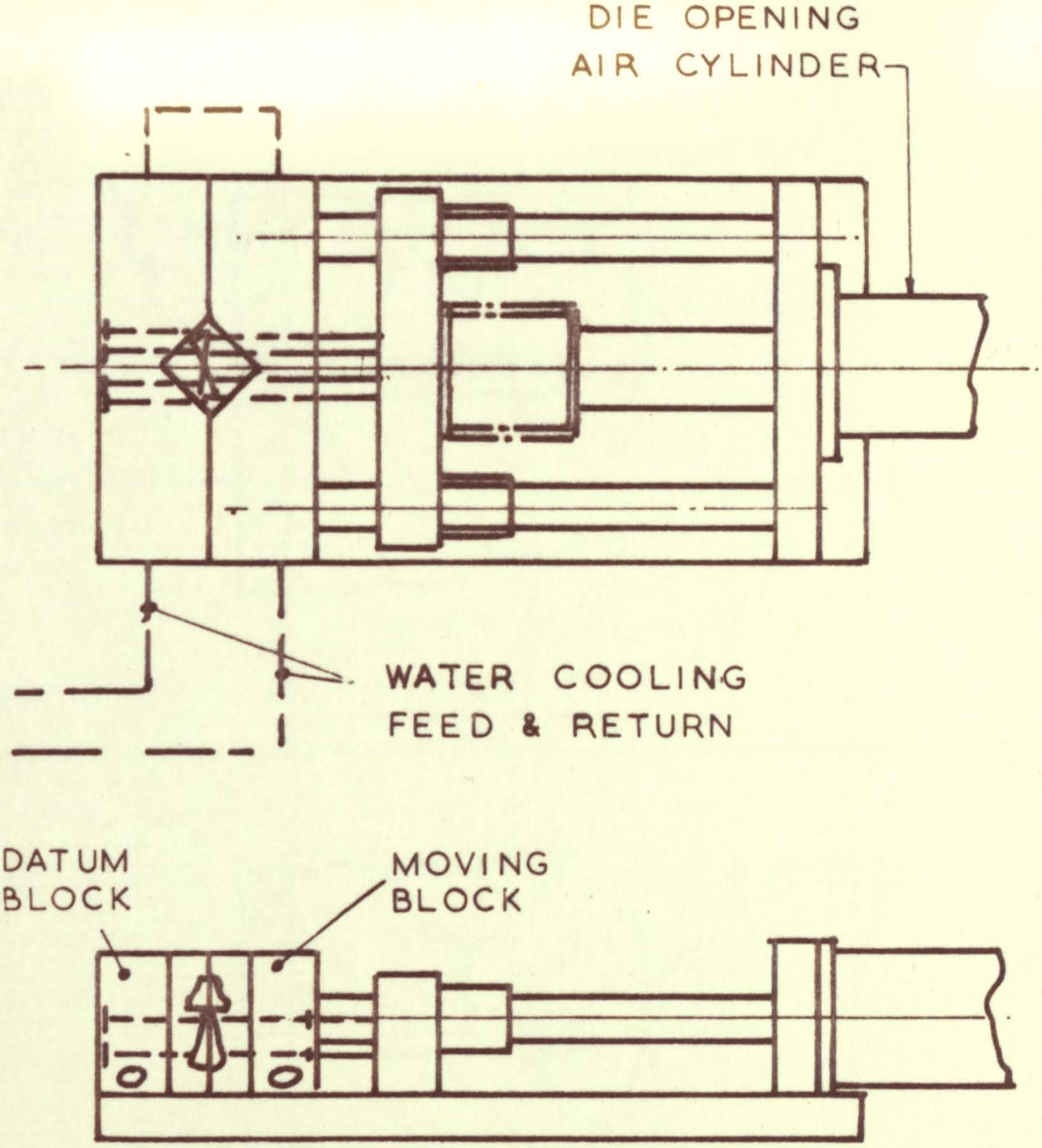


FIGURE 5



TYPICAL
ENCAPSULATION
DIE

FIGURE 6

INSULATED PIN FOR USE WITH USE WITH MIMIC DIAGRAM

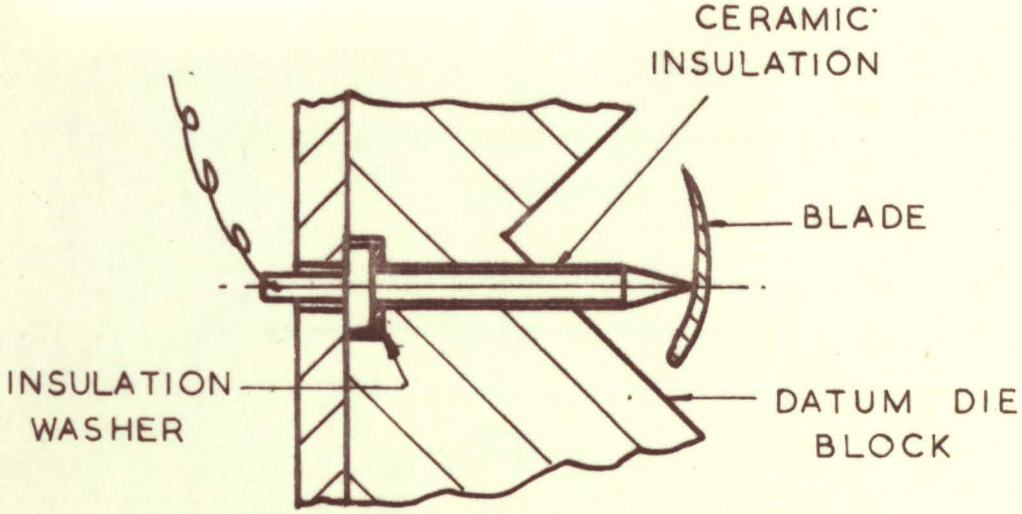
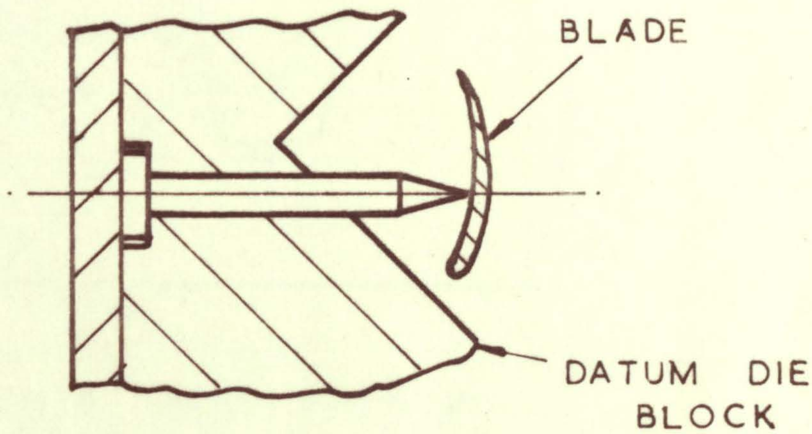


FIGURE 7



NORMAL PIN

FIGURE 8

ILLUMINATED MIMIC DIAGRAM

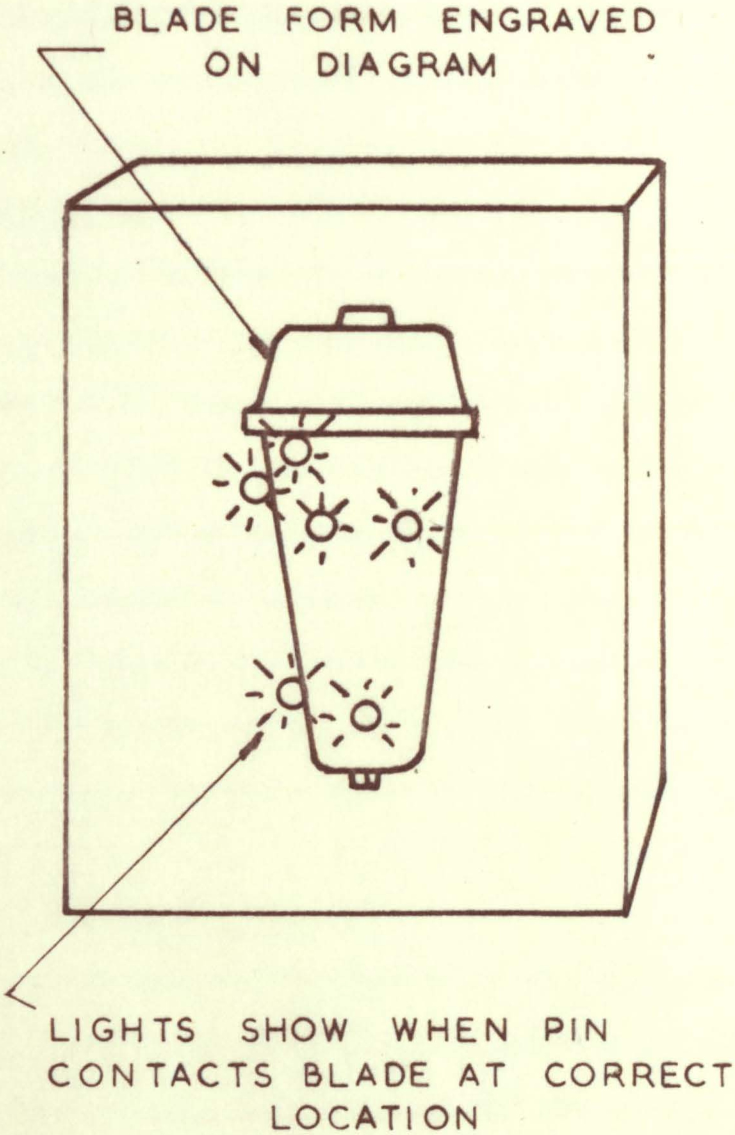


FIGURE 9

blocks. The pins have a small voltage applied to them and when the blade is correctly loaded in the die, the pins are earthed, a relay is operated, and a light on a mimic diagram of the blade locations, illuminates, (Figures 7, 8, and 9).

If the blade is not touching any pin, this is indicated by the corresponding light not being illuminated. An electrical interlock prevents the encapsulating material being cast until the blade is correctly loaded.

2.2.1 Die Material

As the casting temperatures are not very high, the die material does not need to be of the same heat resisting materials used for die casting tools. Dimensional stability is more important, and the most common material is CSM2 (AISI-P20) made by Crusteel Ltd.(Ref.3) or equivalent. This material will not distort during machining or during the encapsulation process.

The die should be designed so that all the encapsulation faces can be surface ground and the location pin holes jig bored or jig ground. Adequate cooling is essential during grinding to prevent distortion.

2.3 The Encapsulating Machine

Attempts to introduce turbine blade encapsulation into the factory as a production process using ladle and bunsen burner have failed. A purpose-built machine with all the control equipment is essential. Cirrus Equipment Ltd. build such machines (Ref.4) and have supplied the majority of blade manufacturers in the Western World.

The usual configuration is as shown in Figure 11. To achieve a cycle time of say 24 seconds, 4 dies would be required, mounted on a rotary turntable with 8 - 45° indexes. The index may be pneumatic, hydraulic or mechanically operated but hydraulic is most common.

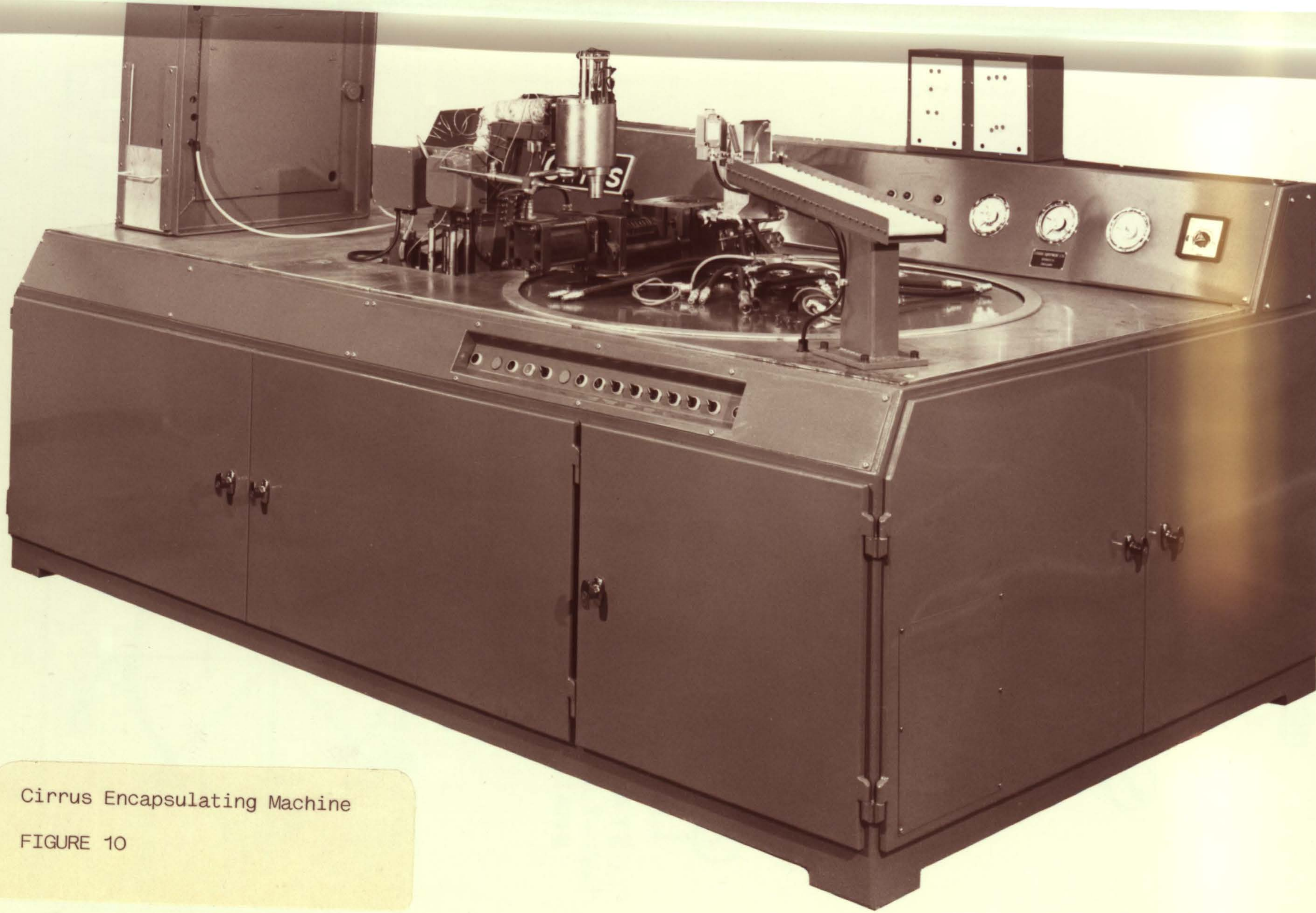
The blade is loaded at position (1) by an operator who is usually only semi-skilled. He, or more frequently she, presses the index button when the blade is correctly loaded, but the index will only take place if a timed interval has elapsed. The blade moves to station (2) under the pouring head containing the reservoir of molten alloy. The pneumatically operated metal-to-metal valve opens and a steel probe moves downwards into the encapsulation cavity. The probe has a 4 volt direct current voltage charge and, when the level of the molten metal reaches it, the probe is earthed, and a relay operates closing the casting valve and retracting the probe.

The die is indexed through stations 3,4,5,6 and 7 during which time the encapsulation is cooling so that when it is at station 8 the die is opened and the encapsulation is ejected down a conveyor and, on an automated production line, into the auto loading device which loads it into the first operation machine.

The pump tank is of stainless steel, with cartridge heaters in the base and sides. The temperature is controlled. The pump is pneumatically operated and is of the reciprocating type.

The piston has cast iron piston rings. The bore is usually about 75mm and the stroke 50mm. Non-return valves in the base of the pump allow metal from the tank to flow in on the up-stroke and the metal to be pumped to the pouring head on the down-stroke.

The molten metal goes through a heated temperature controlled pipe up into the pouring head. The head is heated and temperature controlled and contains sufficient molten metal to make at least one



Cirrus Encapsulating Machine

FIGURE 10

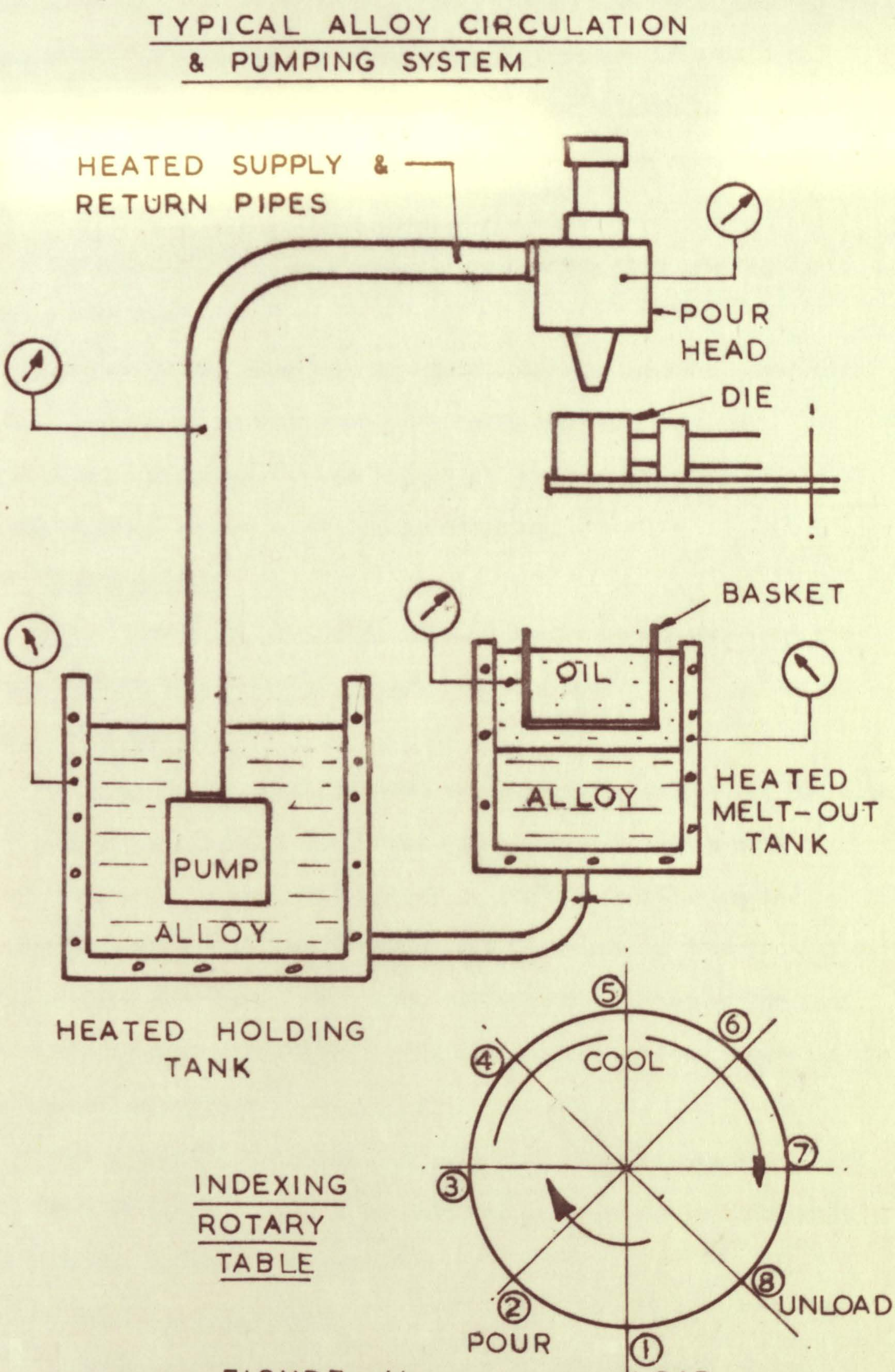

TYPICAL ALLOY CIRCULATION
& PUMPING SYSTEM
HEATED SUPPLY &
RETURN PIPES
POUR
HEAD
DIE
BASKET
OIL
ALLOY
HEATED
MELT-OUT
TANK
PUMP
ALLOY
HEATED HOLDING
TANK
5
6
4
COOL
7
3
INDEXING
ROTARY
TABLE
8
UNLOAD
2
POUR
1
LOAD

FIGURE 11

encapsulation. An overflow pipe takes the surplus metal back to the pump tank. Usually, the pump operates at frequent intervals to circulate the molten metal through the system helping to maintain uniform temperature and avoiding segregation of the constituent metals in the various alloys.

The pump tank and twin pipe to the pouring head are lagged to reduce heat loss.

Coupled to the pump tank by heated pipe is the main reservoir tank. This is of similar construction to the pump tank but considerably bigger. In some installations, the capacity of the reservoir tank can be over 1000 Kg of alloy.

2.4 Decapsulation

After machining, the encapsulation has to be removed from the blade. There are two main methods commonly used:

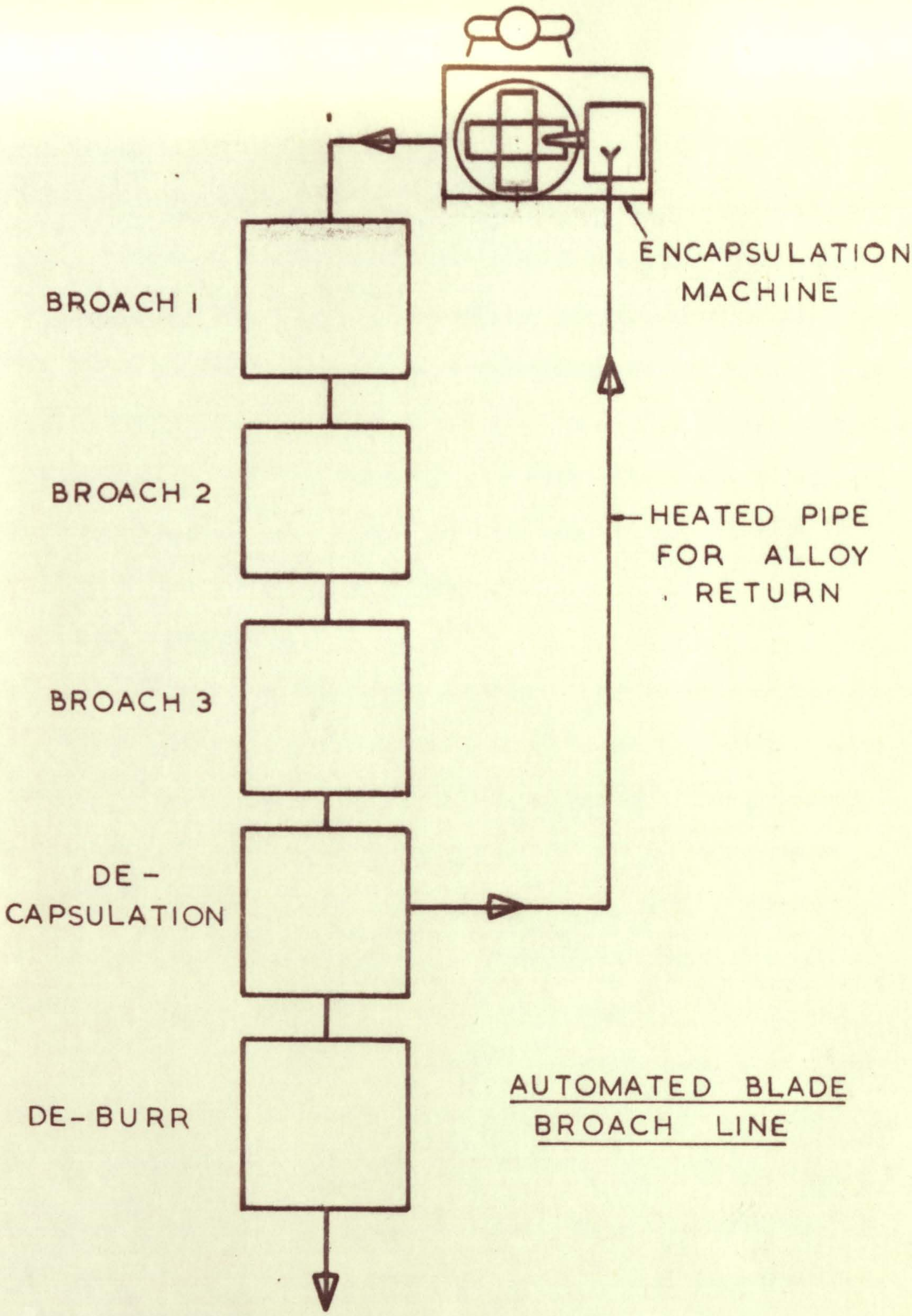
2.4.1 Oil Melt-out

This method is possible with the bismuth-tin alloys but not with the lead based alloys. The former can be lowered into a bath of heat treatment oil at a temperature of 180^{o}C. Oscillating the encapsulation assists heat transfer and the blade is free from alloy within about 6 minutes. The alloy falls to the bottom of the tank and flows by means of a heated pipe back to the reservoir tank in the encapsulating machine. (Figure 12)

Fume extraction equipment is essential above the melt out tank and there is a fire risk. A temperature probe in the oil controls the heating system of the tank.

2.4.2 Mechanical Splitting

In this process the machined blade in its encapsulation is



ENCAPSULATION MACHINE
BROACH I
BROACH 2
HEATED PIPE FOR ALLOY RETURN
BROACH 3
DE-CAPSULATION
DE-BURR
AUTOMATED BLADE BROACH LINE

FIGURE 12

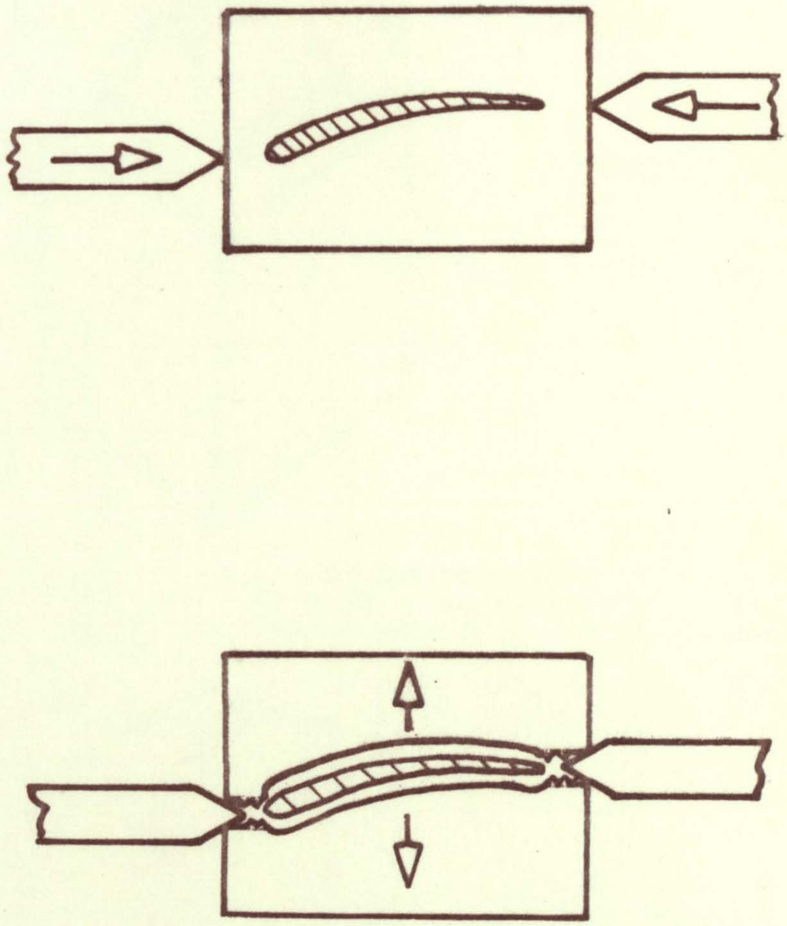
placed between the blades located in line with the loading and trailing edge of the blade. (Figure 13) The jaws are closed hydraulically (with Cerrotru, the bismuth-tin eutectic alloy, a force of 6000 Kgs is necessary) and the block of alloy splits leaving the blade free.

It is important that the jaws are opposite the edges of the blade, otherwise distortion of the blade may result. For dealing with different blades, the positions of the jaws must be adjustable. The splitting device is sometimes situated above the reservoir tank on the encapsulating machine although in an automated system a more logical position is at the end of the line. The piece of encapsulating material falls into a melting tank connected to the encapsulation machine by a heated pipe.

2.5 Swarf Separation

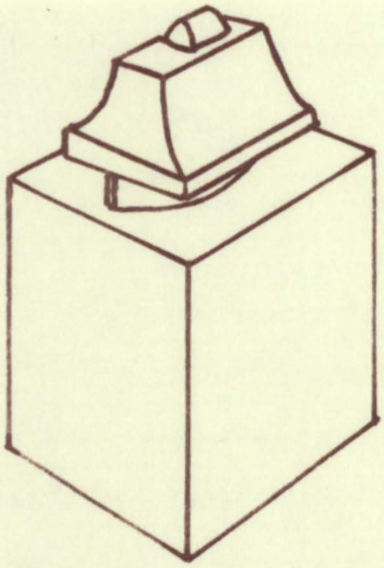
When an encapsulated blade undergoes a grinding operation, it is essential that the grinding wheel does not come into contact with the lead or bismuth based alloy, otherwise clogging of the grinding wheel results. Grinding is used mainly on the turbine blades where heat resisting nickel alloys have to be used. Fortunately the forces involved in grinding are relatively light, and the encapsulation can be clear of the machining area. (Figure 14).

For broaching, which is the most economical method of producing titanium compressor blades, the forces involved are much higher and it is necessary to support the blade root by the encapsulation. It is not unusual to encapsulate the blade completely. (Figure 15). This leads to the production of swarf, which is a mixture of the blade material and encapsulation material. With bismuth currently



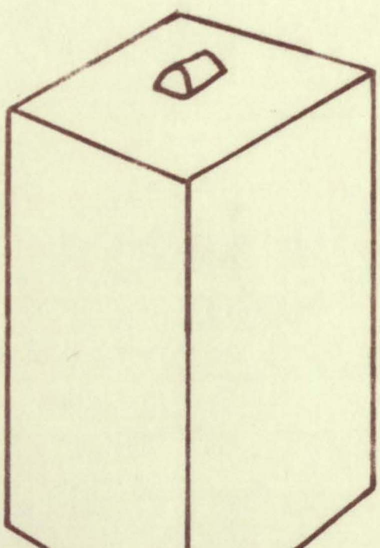
MECHANICAL REMOVAL OF BLADE

FIGURE 13



BLADE ROOT PROUD OF BLOCK FOR GRINDING

FIGURE 14



BLADE COMPLETELY ENCAPSULATED FOR BROACHING

FIGURE 15

costing £8000 per ton, it is essential that the encapsulating material is recovered.

Cirrus Equipment Ltd. did research into this separation problem and found that it was relatively simple to remove 75% of the encapsulation material, but progressively more difficult to remove a greater percentage. The encapsulating alloy adhered to the large surface area of the swarf. Vibration, squeezing and rolling were tried at temperatures above the melting point, but recovery was restricted to less than 70%.

A centrifuge was built, but only 90% recovery was possible.

The Cerrotru and Cerrocast suppliers in the UK, Mining & Chemical Products Ltd., currently take the mixed swarf from the blade manufacturers and recover the encapsulation alloys. The recovery rate they achieve is not known.

Frys Metals Ltd., who supply the lead based alloy Frycap 7, in the UK, do the same service for their customers. Obviously the transport costs are high and a compact process plant for swarf separation is a desirable piece of equipment for the turbine blade industry.

2.6 Encapsulating Materials

2.6.1 Cerrobend and Cerrobase

Cerrobend (composition 50% Bismuth, 27% Lead, 13% Tin, and 10% Cadmium, and melting point 70^{o}C), and Cerrobase (composition 55% Bismuth and 45% Lead, and melting point 124^{o}C), are used for securing turbine blades in cast iron, or cast steel shuttles, (Figure 16). Shuttles are expensive and easily damaged but this method is still used. Pratt and Whitney in Hartford, Connecticut, USA, use this method. They say that their huge investment in shuttles is one reason that the change to shuttleless encapsulation has not been made.

The properties required for the casting material used with shuttles are expansion on cooling, and ease of melting out. Dimensional stability is not important.

2.6.2 Rigidax

Rigidax is a plastic material made by M. Argüeso & Co., Inc. of USA. It has a limited use in blade encapsulation. The distributor in the UK has to refer to the American Company for technical data and this often takes a considerable time.

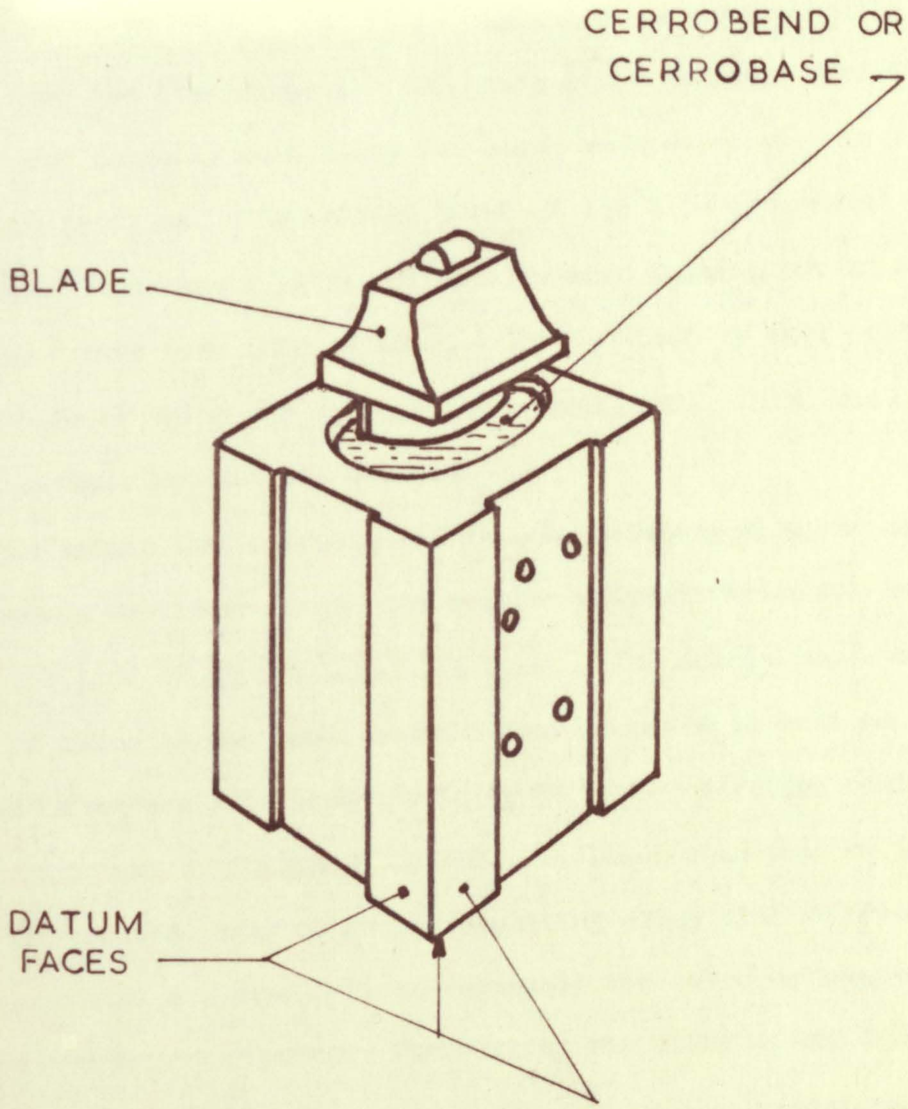
Rigidax is rarely used as a total shuttle-less encapsulating material. It is often used for securing the feet of nozzle guide vanes or similar blades prior to grinding datum faces. The nozzle guide vane is located by means of sophisticated gauging equipment which includes controlling the throat area. This is the minimum area through which the expanded gas goes, when passing between a pair of blades.

To achieve a desired throat area, despite the fact that the length of blade aerofoil will vary from blade to blade, the blade is twisted until a constant reading is achieved. The feet of the blade are then encapsulated and the blade datum machined.

Rigidax can be used for this purpose as dimensional stability is not important. This material possesses the properties of slight expansion on cooling and fairly low melting point, which are necessary for this application. (Ref.5)

2.6.3. Cerrotru

Cerrotru is the trade name of the bismuth-tin eutectic alloy



CAST IRON SHUTTLE

FIGURE 16

produced by Mining and Chemical Products Ltd., Wembley, London. Its composition is 58% Bismuth and 42% Tin. Its melting point is 138°C and its latent heat of fusion is 11.12 K cal/Kg. Its hardness is approximately 22 Brinell and it is claimed to be dimensionally stable over the time range 1 - 100 hours after casting. (Ref.6) It is the most commonly used alloy for blade encapsulation. It is not used with shuttles. The melting point of 138°C is convenient for handling. It presents little difficulty when melting out in oil as the temperature need only be 160°C - 180°C, which is well below the temperature at which the oil quickly breaks down. This leads to long intervals between oil changes.

The latent heat of fusion of an encapsulating alloy is important because the lower it is, the quicker solidification can occur and the cycle time of encapsulation is lower. The energy required to heat the alloy in the tank, and the heat required to melt out the encapsulation are also lower, leading to lower operating costs. The latent heat of fusion of Cerrotru is lower than that of Cerrocast.

The specific heat of an encapsulating alloy also affects the performance of a system. It is desirable for it to be low, so minimising the amount of energy for heating the alloy in the machine when starting up and also reducing the die cooling necessary. The specific heat of Cerrotru is 0.045 which is slightly lower than that of Cerrocast.

Cerrotru is very satisfactory for use in encapsulating systems but has one major disadvantage. It is very expensive. It is a major cost when setting up the system and its high cost may also lead to pilfering.

Some users have also reported another disadvantage. They say that blades have loosened in the encapsulation block during machining.

2.6.4 Cerrocast

Cerrocast is similar in many aspects to Cerrotru but is non-eutectic. Its composition is 40% Bismuth and 60% Tin, making it tin rich compared to Cerrotru. The cost is slightly less being currently £9,500 per ton compared to £10,100 per ton for Cerrotru.

The latent heat of fusion of Cerrocast is 12.23 Kcal/Kg and its specific heat is 0.047. Its hardness is approximately 22 Brinell.

Cerrocast is claimed by its makers to be dimensionally stable, with a slight shrinkage after casting. Users of the alloy claim that Cerrocast has good holding properties and will hold the blade better than Cerrotru. The reports on this have not, however, been consistent.

The melting temperature of Cerrocast makes the encapsulating machine more troublesome. The alloy oxidises more than Cerrotru and segregation of the tin can occur. Melt out is carried out at a higher temperature than Cerrotru, and oil life is shorter. Because the casting temperature is 180^{o}C, the blade reaches a higher temperature before solidification occurs, and distortion occurs during cooling due to the shrinkage of the blade. The encapsulating block changes dimensionally only very slightly.

2.6.5 Lead Based Alloys

The most commonly used alloy of this type is Frycap 7 made by Frys Metals Ltd. (Ref.7)

Its composition is 79% Lead, 14% Antimony. 6% Tin and 1%

Bismuth. The latent heat of fusion and specific heat are not published and this information would not be divulged by Frys Metals Limited for commercial reasons. Very simple experiments could be performed however, to obtain such data.

Frycap 7 is used in the pressure casting system developed by Fisher of Canada. This system is limited to large production runs of blades. Frycap 7 is also used in the gravity cast encapsulation and its use in this system will be considered here.

Frycap 7 is considerably cheaper than the Cerro alloys. Its melting point is much higher(243^{o}C) however, and this makes the handling and the control of the alloy more difficult.

With the higher melting point of Frycap 7, greater distortion of the blade will occur during encapsulation. Depending upon the tolerances required, this distortion may or may not be significant.

2.6.6 Choice of Encapsulating Materials

When using shuttles, Cerrobend and Cerrobase are available and give good results. The current price of £7.200 for Cerrobase and £7.800 for Cerrobend are within 10% of each other, and the slightly lower cost of Cerrobase is offset to some extent by the need for oil melt out rather than water melt out. The use of shuttles is becoming obsolete and hence the problem of selection of the alloy will soon be academic only.

Rigidax has specific applications particularly where the danger of residual encapsulating material in blade cooling holes precludes the use of Cerro alloys. Its low conductivity and high specific heat do make the encapsulating cycle excessively long, and its use as a total encapsulation material is very limited.

When totally encapsulating the blade, i.e. without using shuttles, the choice between Cerrocast, Cerrotru and Frycap 7 is often based on insufficient information.

To make the choice of materials more objective, it is intended as part of this thesis to examine the properties of Cerrotru, Cerrocast, and Frycap 7, that are necessary for a good, economic encapsulation production process.

The requirements of a good encapsulating material for use without shuttles, are:

(1) Dimensional Stability

(2) Hardness

(3) Good blade holding properties

(4) Ease of casting

(5) Ease of decapsulating

(6) Ease of swarf reclamation

(7) Low cost

In this thesis it is intended to examine properties 1, 2 and 3 of three commonly used alloys - Cerrocast, Cerrotru and Frycap 7 and to examine the effects on these properties of:

a) variation of die temperature

b) variation of casting temperature

c) elapsed time after casting

It is hoped that the results will enable the choice of encapsulation material to be made objectively with resultant advantage to the user.

3 RESEARCH INTO THE PROPERTIES OF VARIOUS ALLOYS TO ESTABLISH THEIR COMPARATIVE SUITABILITY FOR THE ENCAPSULATION OF TURBINE BLADES

3.1 Objectives

a) To examine three desirable physical properties of three alloys commonly used in the encapsulation of turbine blades and to determine whether these properties vary with time. These three properties are:

a) Dimensional Stability

b) Hardness

c) Security of blade holding

The three alloys are:

i) Cerrotru

ii) Cerrocast

iii) Frycap 7

b) To establish what effect variation in the molten metal temperature has on the physical properties.

c) To establish what effect variation in the die temperature has on the physical properties.

3.1.1 Dimensional Stability

Close dimensional tolerances are necessary for turbine blades in order for the gas turbine engine to perform at its designed efficiency. An encapsulating process must be capable of maintaining these tolerances with minimum scrap. Compressor blades cost between £25 & £300 each and there are several thousand in each engine. The scrapping of a blade because of dimensional inaccuracy is therefore very expensive.

For these reasons, the encapsulating material must take up the minimum part of the tolerance available. The material must reproduce consistently the dimensions of the die and these dimensions must remain constant as time elapses.

Most materials undergo crystalline change after casting and this change can take place at varying times. These crystalline changes produce dimensional changes which, for normal castings, are insignificant, but for encapsulating turbine blades, may be very significant.

Given a die, a blade and a certain ambient temperature, the three variables which could be expected to affect the metallurgical condition of the casting are:

a) Molten metal temperature at time of pouring

b) Die temperature at time of pouring

c) Rate of cooling after casting

The rate of cooling is usually determined by the encapsulating machine system. For the tests the sample die was allowed to cool in the ambient room temperature prevailing. This is not ideal and will have to be considered when interpreting results.

The die temperature and the molten metal temperature are, in the author's experience, varied indiscriminately in most blade production factories. How important this factor is will be investigated.

3.1.2 Hardness

The encapsulating material has to support the blade and to resist machining loads. In most cases the blade being machined imposes a compressive load on the encapsulating alloy. Measuring the hardness of the material gives an approximation of both the compressive and tensile strength of the material. The constraints of cost and time preclude measuring all three properties and in a more extensive study it may be desirable to measure, not only these three but others, such as creep and resistance to bending.

3.1.3 Security of Blade Holding

A problem which occurs when using encapsulating techniques is that the blade becomes loose during machining. This leads to scrapping of blades and tool breakage. Some blades with a twisted aerofoil are ideal for secure holding but others are almost flat and tapered and these are difficult to retain.

The encapsulating alloy should have the property of gripping the blades and a simple test was performed to check this capability.

3.1.4 Material Stability

Because encapsulating materials are expensive, it is usual for encapsulations to be machined fairly soon after casting. This enables the machined blade to be decapsulated and the alloy returned to the encapsulating machine for producing new encapsulations.

It is usual to wait until the encapsulation is at room temperature before machining, to remove the error due to thermal expansion of the blade and alloy. The first measurements were made one hour after casting for this reason.

The second set of readings were taken 5 hours after casting, and the final set 28 hours after casting. These three times span the normal production times and interpolation should be possible with low risk error.

3.2 Experimental Equipment

3.2.1 Alloy Melting

The equipment is shown in Figure 17. An electrically heated tank capable of melting 5Kg of alloy is supported on pivot points. A handle on the tank enables it to be tipped on the pivot points to the pour position. Temperature control is by means of a 0 - 350°c temperature controller.

3.2.2 Die

Figures 19 & 20 show the test die. The length is nominally 150mm with the two end faces ground parallel. Spring loaded end plates form the ends of the die. A temperature probe is inserted into the base of the die. A top block is placed in the die below the casting level before pouring, to produce a parallel surface for hardness testing. Two ejector pins are in the base of the die.

In each end plate a ground pin is placed before each cast. The length of pin protruding into the die is controlled, and the die is designed so that these two pins are cast into the block and are removed with the block, after casting. (Figure 20).

The die is made of mild steel and the pins of 8mm silver steel.

3.2.3 Length Measuring Equipment

It is normal practice when designing encapsulation dies to assume that the encapsulation will be exactly the same size as the cavity in the die when at room temperature. The die cavity dimensions will of course, vary with the die temperature, and the encapsulation will freeze when the alloy is at its melting point and the die is at some temperature below this.

The encapsulation length can be compared to:

(a) the ambient temperature die length

ALLOY MELTING & DIE FILLING EQUIPMENT

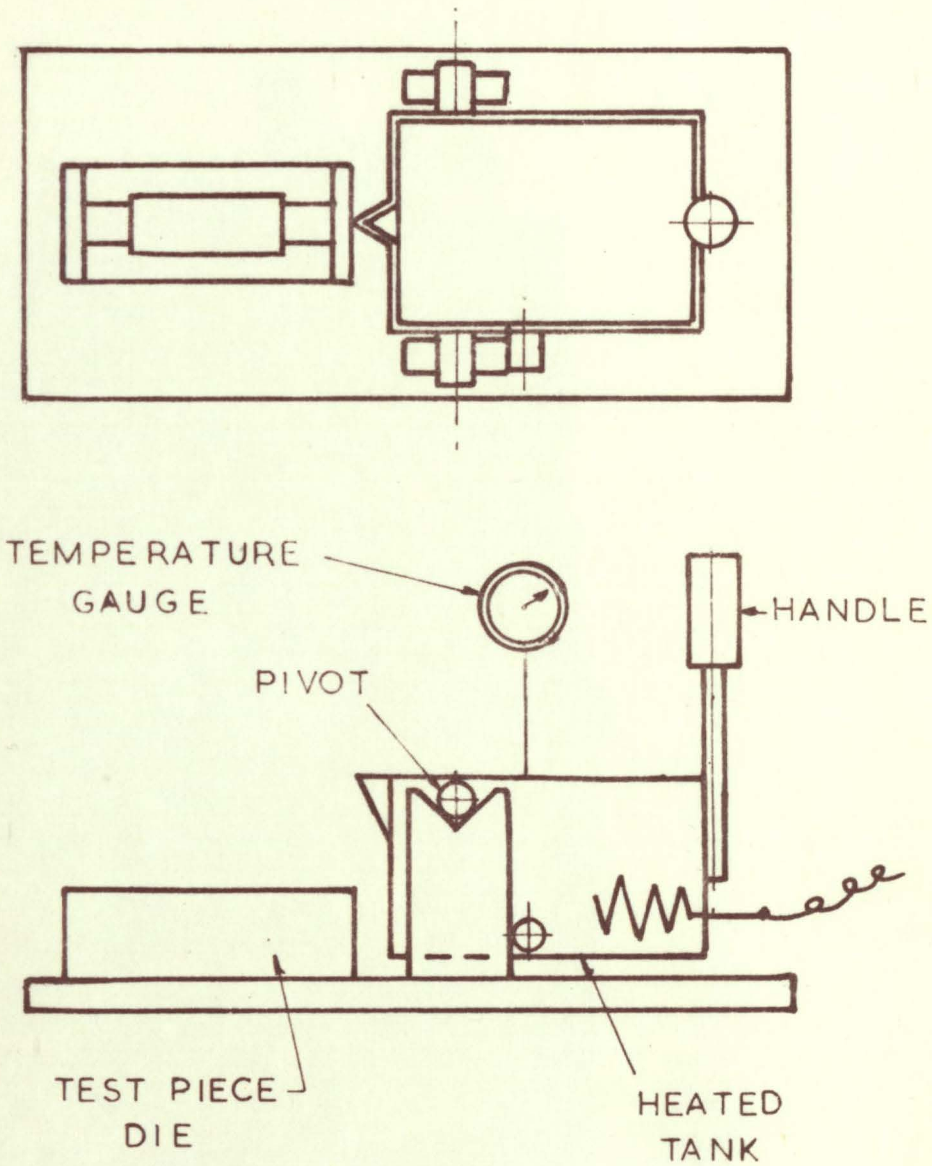
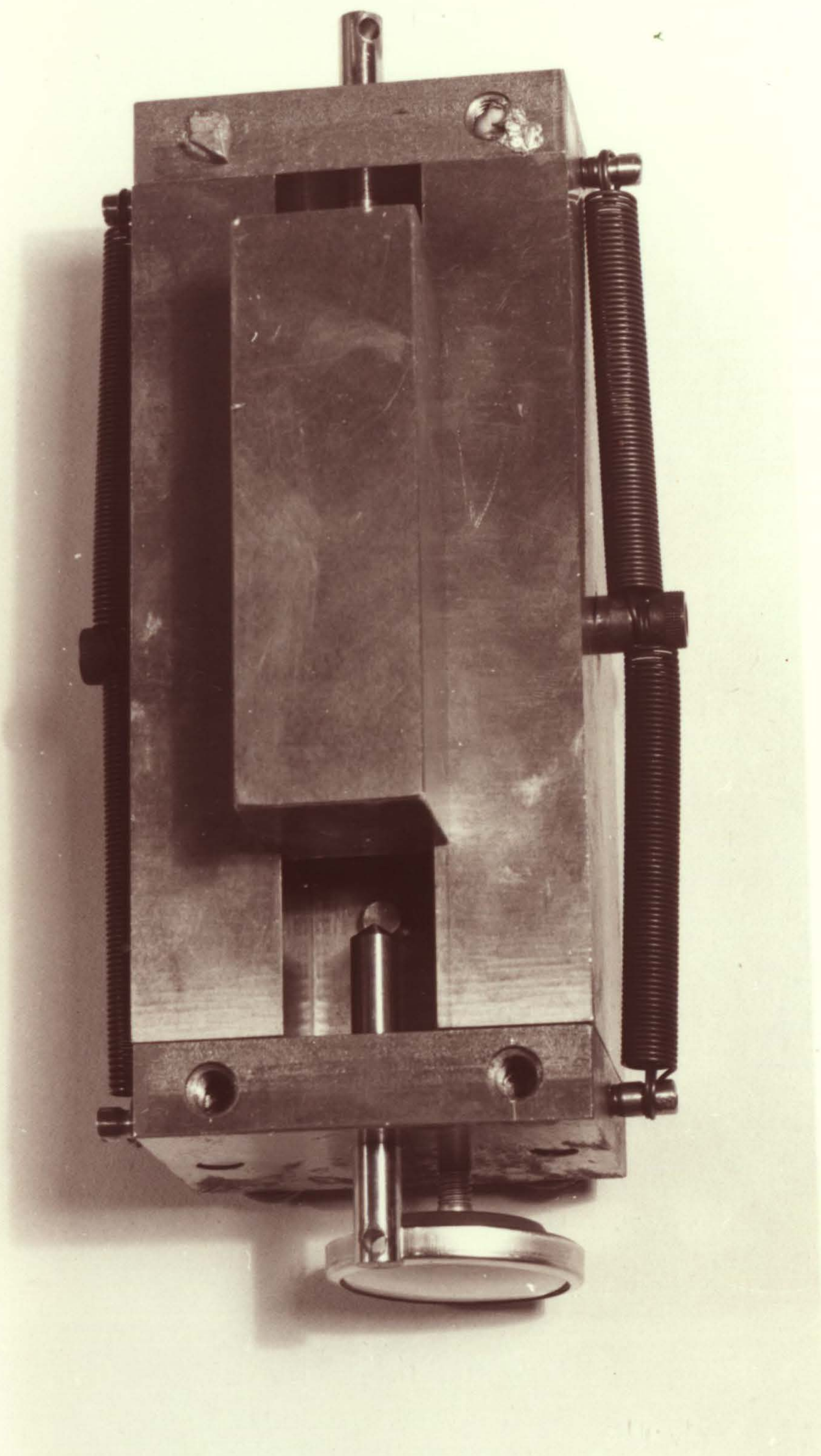
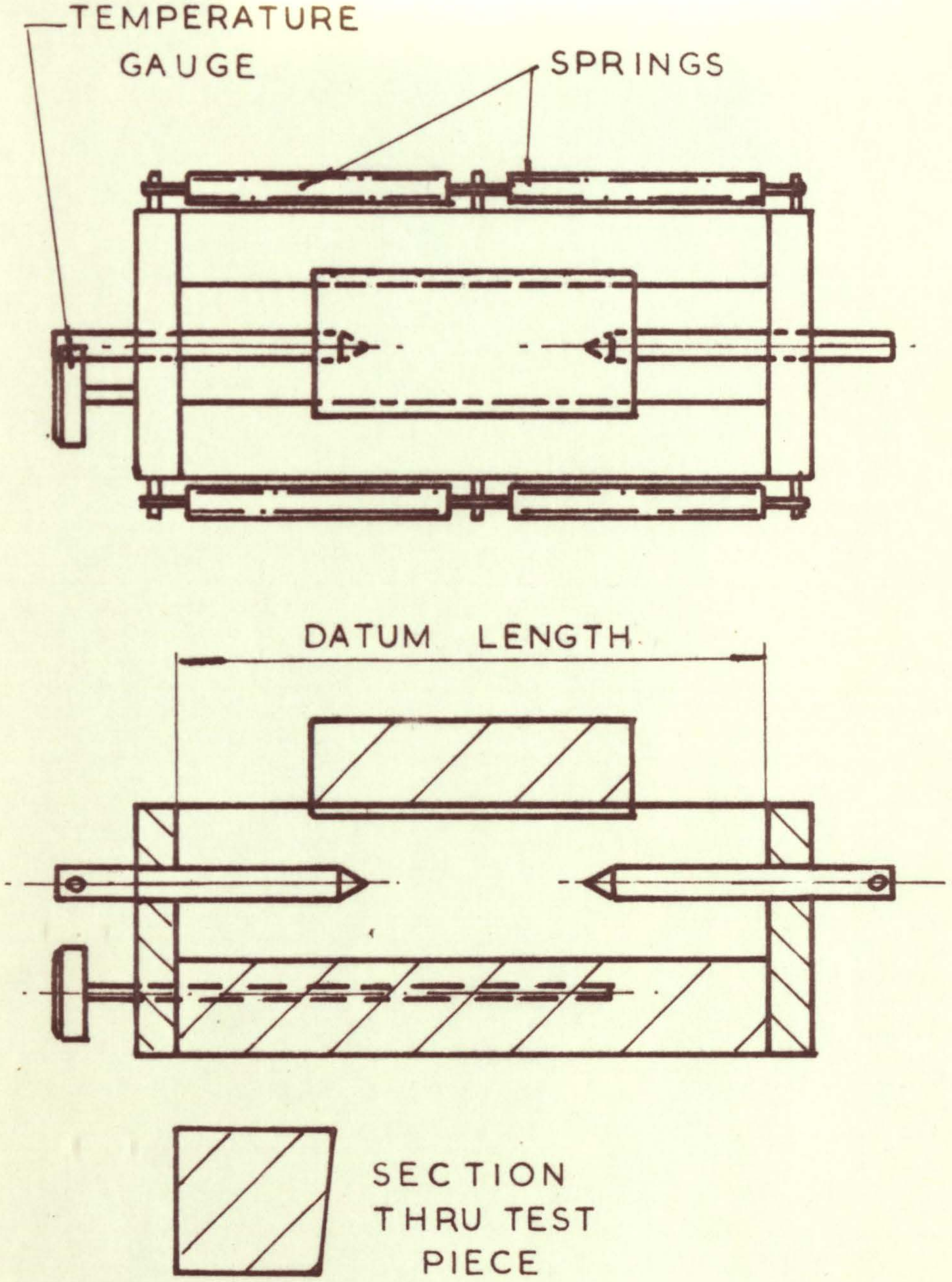


FIGURE 17

Test Die

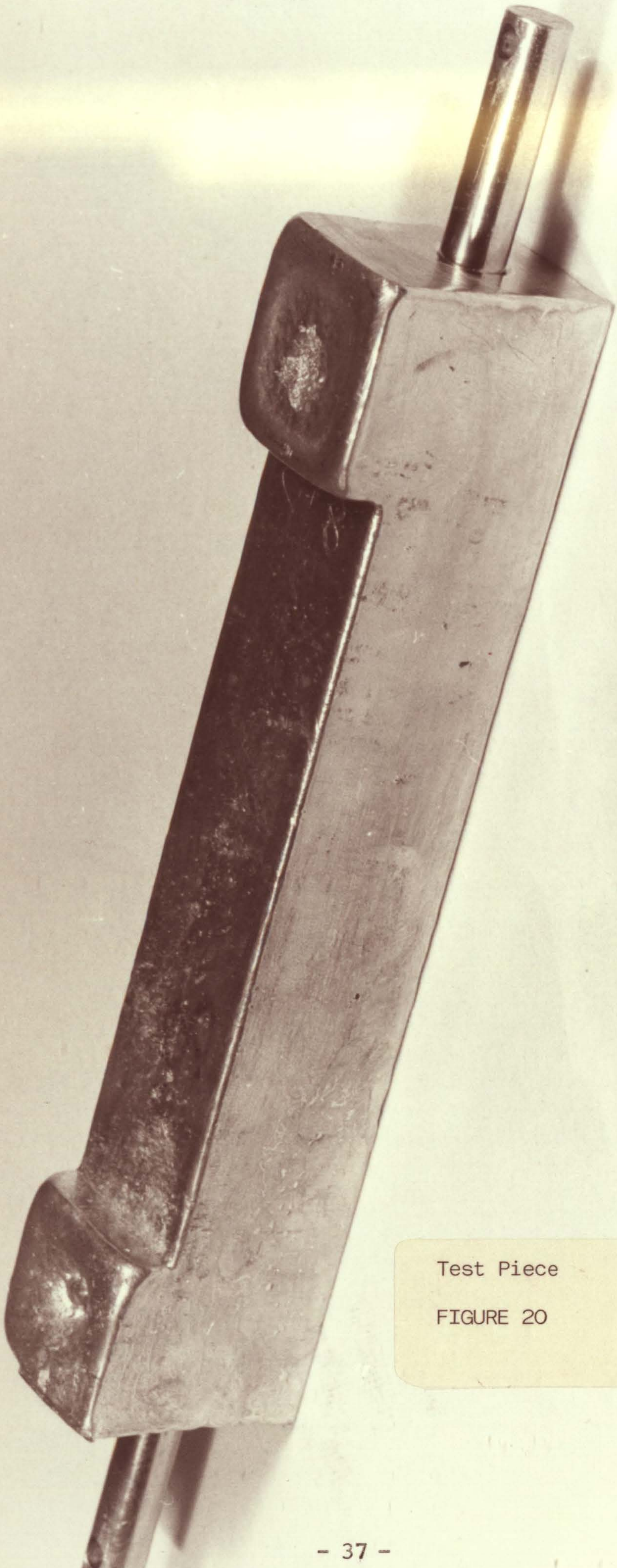
FIGURE 18





TEST PIECE DIE

FIGURE 19



Test Piece

FIGURE 20

(b) the die length at the temperature at which the die is maintained prior to casting

(c) the die length at the temperature which the die reaches at the time of solidification

Additionally, the encapsulation lengths measured at the three times can be compared to each other.

To enable (c) above to be done, the die temperature at solidification was recorded.

The necessary equipment is shown in Figure 21. A .002mm dial gauge, used with slip gauges, was used for length measurement. A hole in the base of the surface plate allowed measurements to be carried out with the pin still in position in the test block.

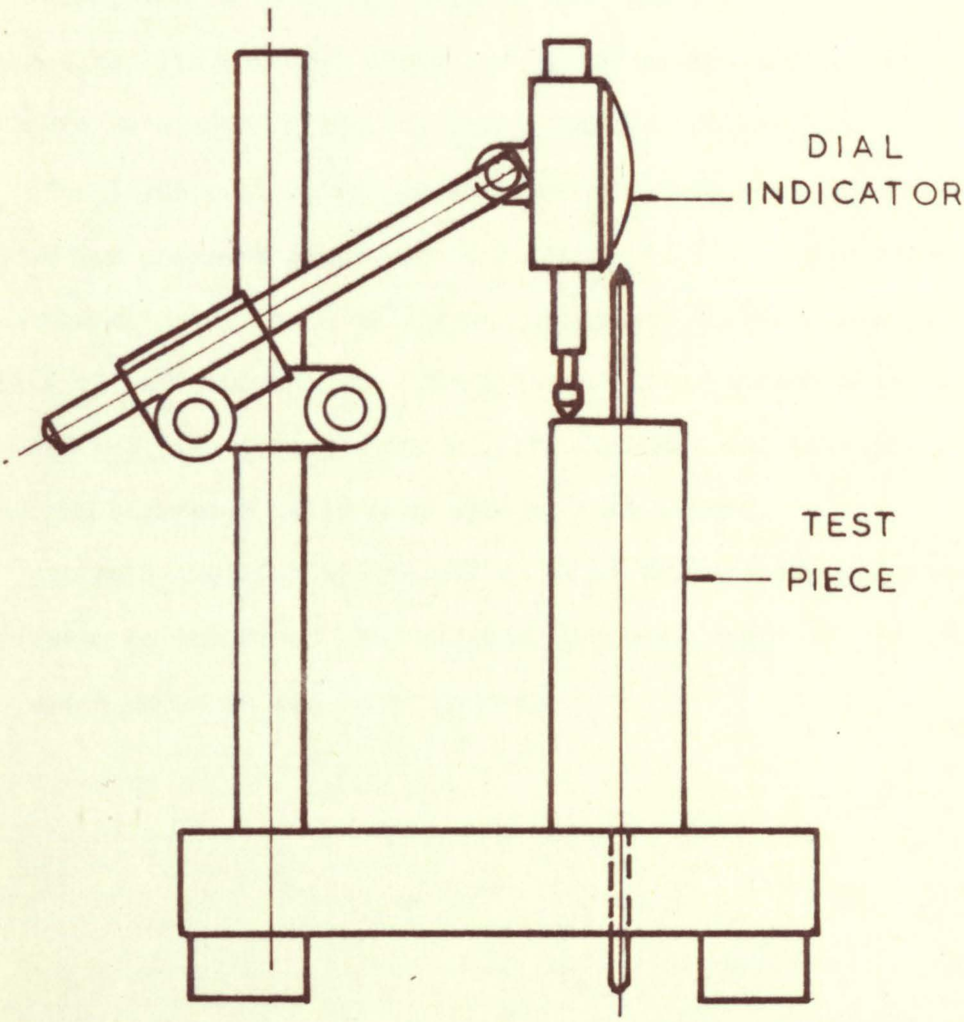
3.2.4 Hardness Testing

Because the three alloys being evaluated are known to 'creep', the method of hardness testing had to be chosen with care.

A Rockwell Hardness Tester using a ¼" diameter ball was chosen. The 60 Kg weight was used, giving results on the L scale of hardness.

A technique developed for use with plastic materials overcame the problem of the ball continuing to indent under load indefinitely due to 'creep'. The test piece was placed on the anvil, the load applied for 15 seconds, the load removed, and the hardness reading taken after 15 seconds. (Ref.8)

The test pieces, being castings, suffered from casting marks, and it was felt necessary to take 5 hardness readings and take the average, to overcome this problem. The standard deviation was calculated in each case to check consistency of readings.



DATUM LENGTH
CHECKING APPARATUS

FIGURE 21

3.2.5 Holding Force

The two pins in each block were each pulled at one of the three test times. As each test was replicated, it was possible to pull one pin at each of two times and two pins at the other time.

For loads up to 50 Kg, weights were suspended on the pin to be pulled with the test block restrained by the support frame. Weights were added gradually until the pin pulled (Figure 22).

For loads over 50 Kg, an air cylinder with pressure reducing valve and pressure gauge was used. (Figure 22). The air cylinder was connected by means of the crosshead and the pressure increased until the pin pulled out. The pressure times piston area minus piston rod area gave the force. An allowance was made for friction and the apparatus calibrated against dead weight.

In case the pins at the end at which the casting was poured differed to the other pin, all the pins were numbered and the end at which each pin was cast, recorded.

PIN WITHDRAWAL RIG

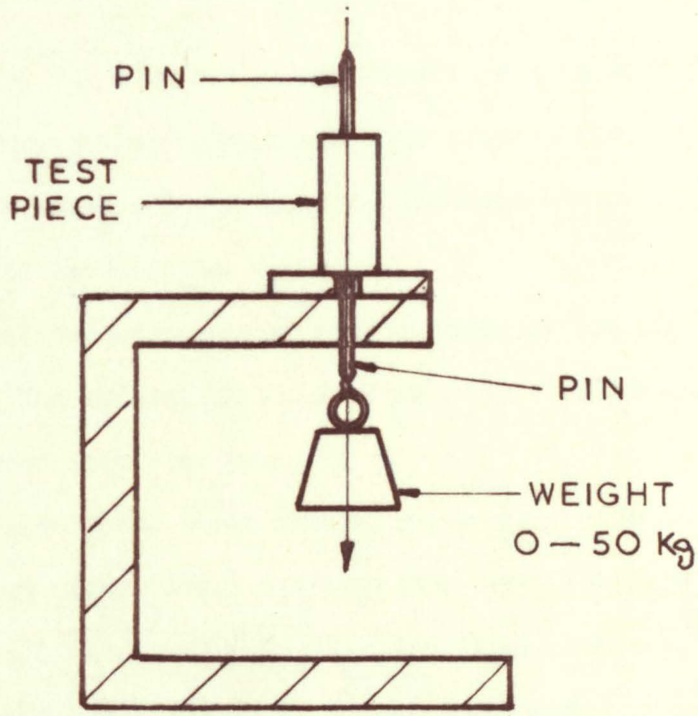
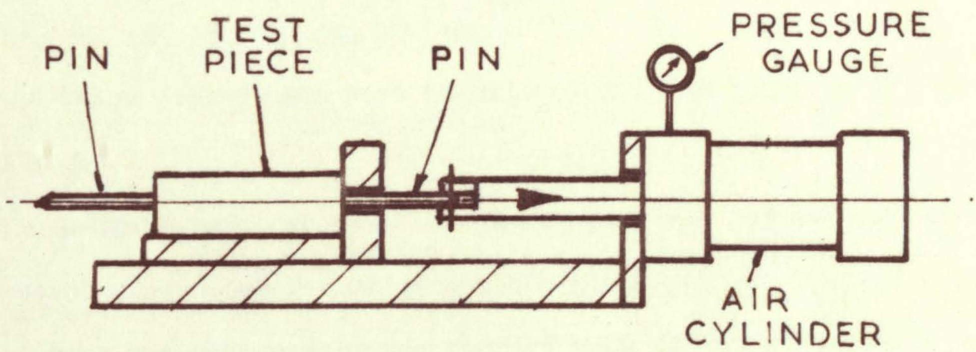


FIGURE 22



FOR LOADS 50 — 300 Kg

PNEUMATIC PIN WITHDRAWAL RIG

FIGURE 23

3.3 Experimental Procedure

For each alloy a 3 x 3 factorial experiment was performed. Replication of the hardness results and the dimensional stability results was possible but the pin-pulling results were not replicated.

Statistically a 3 x 3 factorial experiment is very powerful, with all the readings being fully used. The significance of the results of both the main effects, and the interactions between the main effects can be established.

The statistical analysis carried out is based on the work by Davies (Ref. 9). The assumption is made that the results are normally distributed about the mean.

For testing each of the three alloys, three die temperatures were used and three molten metal temperatures, with readings taken at three different times, giving 3 x 3 x 3 = 27 experiments. Each one was replicated so that the total experiments numbered 54. The results of each experiment were recorded and analysed. A summary of the results for each alloy was made and these are shown on pages 46, 51, 56, 60, 65, 70, 74, 79, 84.

The three alloys used were metallurgically analysed before the tests began.

The ambient temperature of the laboratory was kept as constant as possible, but some variation was unavoidable. The ambient temperature was recorded at the time of each cast and at each reading.

The hardness test was performed 5 times at each test time, but if a 'rogue' result occurred then it was repeated and the 'rogue' result discarded. This was done, as it was considered that the ball of the Rockwell hardness tester could encounter a 'fold' in the surface of the casting.

Care was taken when changing the alloy in the melting tank, to remove all traces of the previous alloy, to avoid contamination.

3.4. Temperature - Length Calibration of Die

TEMP °C	30	35	40	45	50	55	58
DIE LENGTH 150+ MM	.026	.040	.048	.061	.075	.087	.094

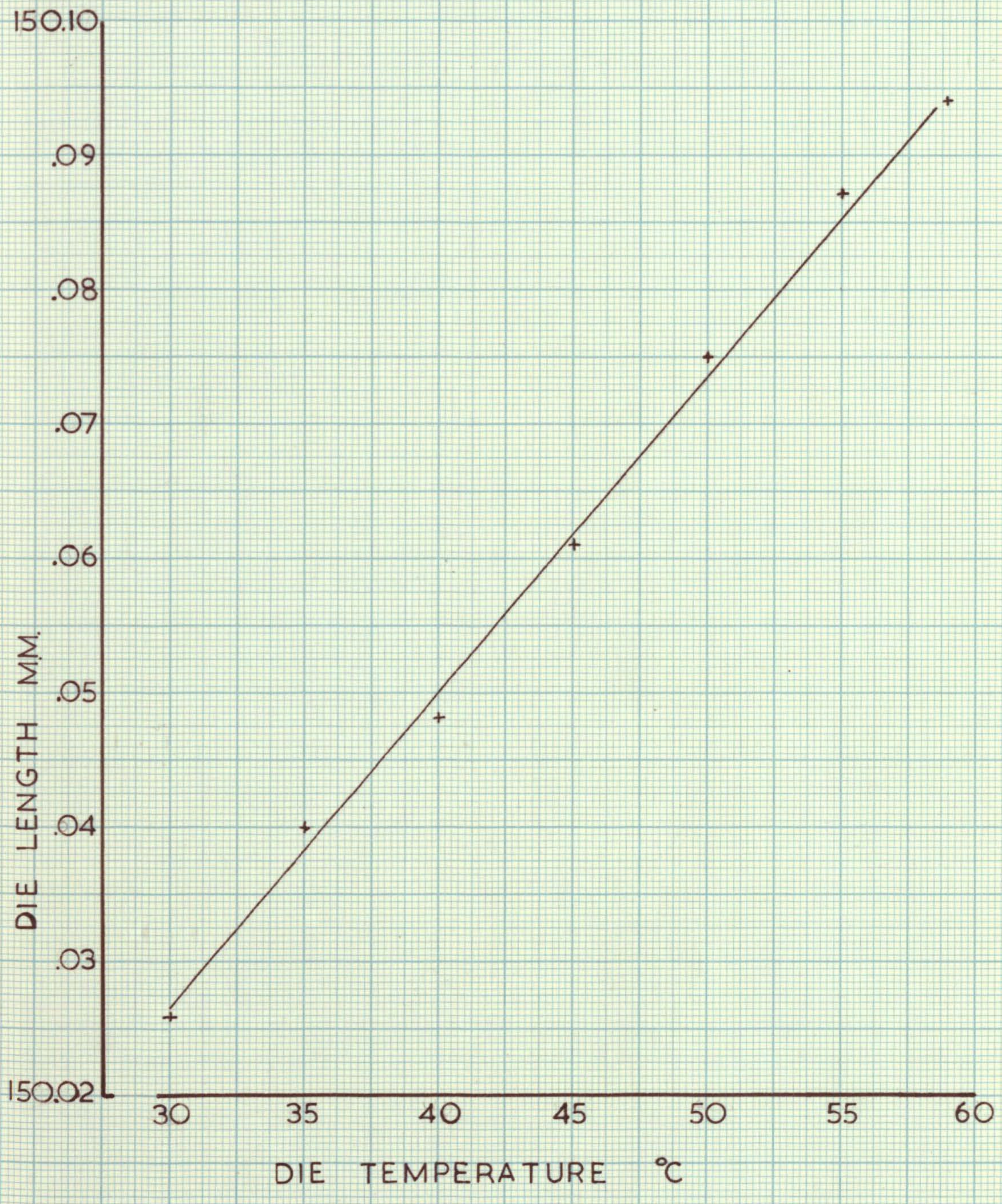


FIGURE 24

3.5 Metallurgical Analysis

It was important to establish the composition of the Cerrotru, Cerrocast and Frycap 7, so that comparisons can be made with the experimental work.

Mining and Chemical Products Ltd undertook the metallurgical analysis of the alloys used in the experiments. The results are as follows:

CERROTRU:	Bismuth	57.34%
	Tin	42.62%
	Lead	0.04%
CERROCAST:	Bismuth	39.85%
	Tin	60.10%
	Lead	0.05%
FRYCAP 7:	Lead	78.34%
	Antimony	14.16%
	Tin	6.17%
	Bismuth	1.27%
	Copper	0.06%

3.6.1. ALLOY:- Cerrotru TEST:- Hardness Rockwell 'L' scale		DIE TEMPERATURE ^{o}C								
		30 D_o			45 D_1			60 D_2		
TIME AFTER CASTING		ALLOY TEMP. ^{o}C			ALLOY TEMP. ^{o}C			ALLOY TEMP. ^{o}C		
		150 A_o	175 A_1	200 A_2	150 A_o	175 A_1	200 A_2	150 A_o	175 A_1	200 A_2
1 HOUR T_o	REPLICATE 1	67.30	70.76	75.88	69.98	71.22	77.22	71.98	77.10	78.48
	REPLICATE 2	68.64	71.54	75.82	69.70	72.12	78.00	74.14	75.88	80.04
	RANGE	1.34	0.78	0.06	0.28	0.90	0.78	2.16	1.22	1.56
	AVERAGE	67.96	71.17	75.85	69.84	71.67	77.61	73.06	76.49	79.26
	SUM	135.94	142.30	151.70	139.68	143.34	155.22	146.12	152.98	158.52
5 HOURS T_1	REPLICATE 1	69.54	71.52	76.02	71.18	74.10	77.84	74.90	77.62	78.08
	REPLICATE 2	69.60	71.00	74.90	70.58	73.66	77.54	73.88	77.28	79.54
	RANGE	0.06	0.52	1.12	0.60	0.44	0.30	1.02	0.34	1.46
	AVERAGE	69.57	71.26	75.46	70.88	73.88	77.69	74.39	77.45	78.81
	SUM	139.14	142.52	150.92	141.76	147.76	155.38	148.78	154.90	157.62
28 HOURS T_2	REPLICATE 1	69.68	72.80	76.28	70.80	74.40	76.30	72.44	76.70	76.88
	REPLICATE 2	70.84	70.46	75.28	70.24	74.78	76.90	74.34	76.86	76.74
	RANGE	1.16	2.34	1.00	0.56	0.38	0.60	1.90	0.16	0.14
	AVERAGE	70.26	71.63	75.78	70.52	74.59	76.60	73.39	76.78	76.81
	SUM	140.52	143.26	151.56	141.04	149.18	153.20	146.78	153.56	153.62

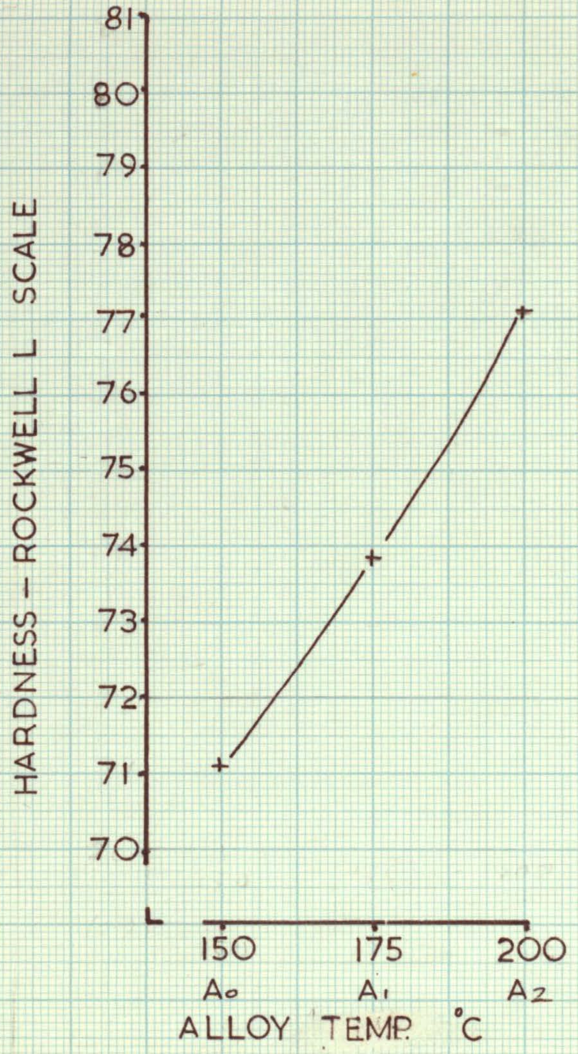


FIGURE 25

FIGURE 26

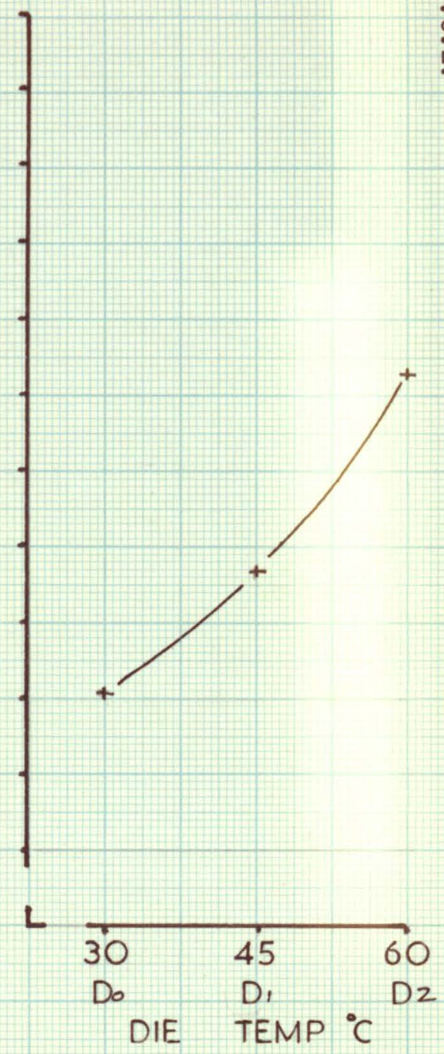


FIGURE 27

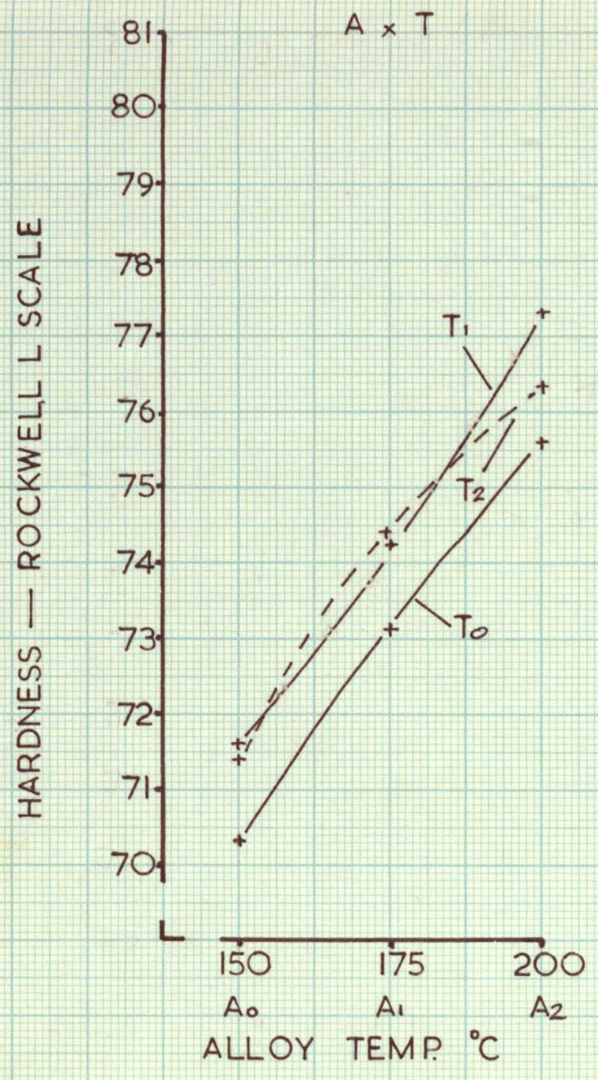


FIGURE 28

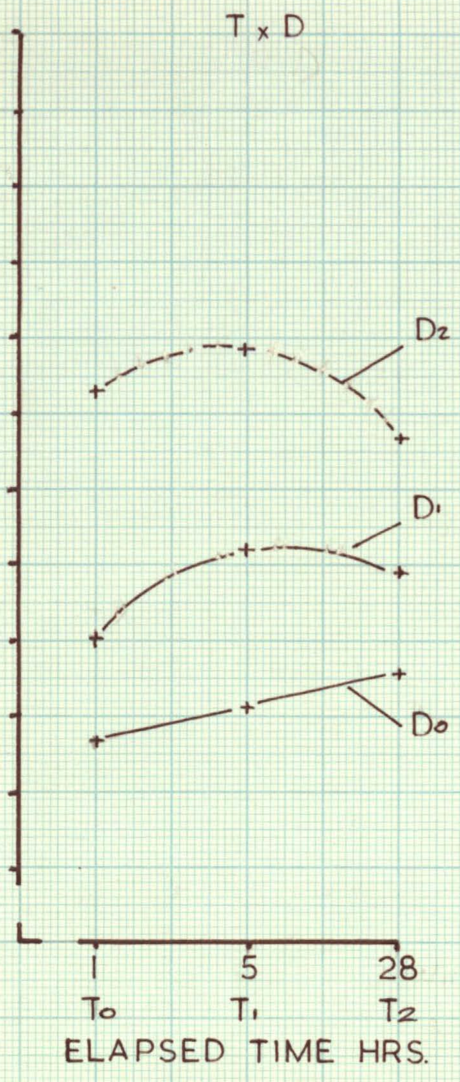


FIGURE 29

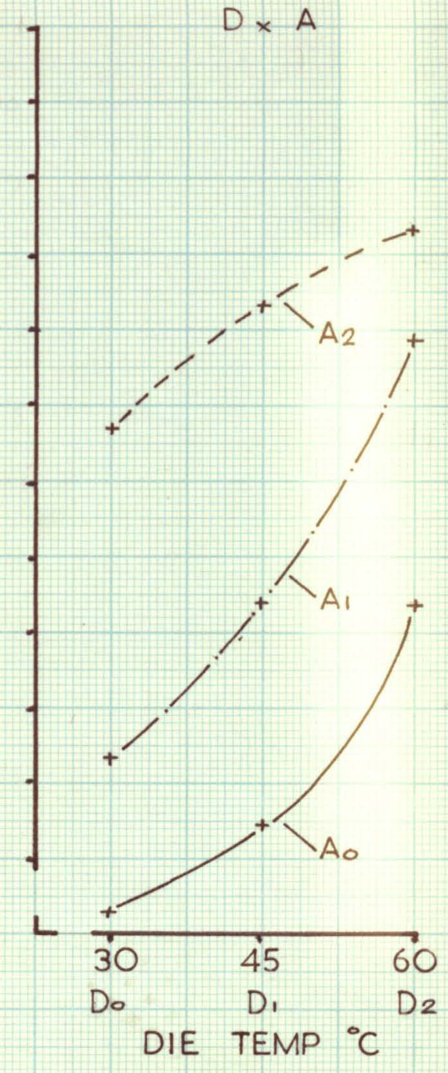


FIGURE 30

3.6.4 Significance of Results

3.6.4.1 Hardness v Alloy Casting Temperature - Figure 25

Statistical significance of results - greater than 99%.

Higher pour temperatures result in increased hardness in the cerrotru.

Hardness in the encapsulation is desirable but higher pour temperatures lead to greater oxidation of the alloy and possible distortion of the blades during cooling.

3.6.4.2 Hardness v Time after Casting - Figure 26

Statistical significance of results - greater than 95%.

After casting, hardness of the Cerrotru rises, reaches a peak at about 10 hours, and then falls. The total change in hardness in this time is small; less than 1 on Rockwell 'L' scale.

3.6.4.3. Hardness v Die Temperature at Cast - Figure 27

Statistical significance of results greater than 99%.

Higher die temperatures result in increased Cerrotru hardness.

3.6.4.4 Interaction between Alloy Casting Temperature and Time after Casting - Figure 28

Statistical significance of interaction - greater than 99%.

There is a very strong interaction. For example

Cerrotru cast at 200°C is harder at 5 hours after casting than at 28 hours after casting, but for Cerrotru cast at 175°C the reverse is true.

3.6.4.5 <u>Interaction between Die Temperature and Time after Casting - Figure 29</u>

Statistical significance of interaction - greater than 95%.

There is an interaction. For cerrotru cast into the die at 30°C, the alloy is harder after 28 hours than after 1 hour, but for cerrotru cast into the die at 60°C the alloy is harder after 1 hour than after 28 hours.

3.6.4.6 <u>Interaction between Die Temperature and Alloy Casting Temperature - Figure 30</u>

Statistical significance of interaction - greater than 99%.

There is a very strong interaction. For an increase in die temperature, the rate of increase in hardness is increasing for the cerrotru cast at 150°C but is decreasing for the Cerrotru cast at 200°C.

3.7.1. ALLOY:- Cerrotru TEST:- Length change mm 150mm +		DIE TEMPERATURE °C								
		30 D_0			45 D_1			60 D_2		
TIME AFTER CASTING		ALLOY TEMP. °C			ALLOY TEMP. °C			ALLOY TEMP. °C		
		150 A_0	175 A_1	200 A_2	150 A_0	175 A_1	200 A_2	150 A_0	175 A_1	200 A_2
1 HOUR T_0	REPLICATE 1	0.104	0.105	0.148	0.104	0.110	0.114	0.088	0.176	0.107
	REPLICATE 2	0.106	0.098	0.138	0.105	0.105	0.108	0.076	0.192	0.092
	RANGE	0.002	0.007	0.010	0.001	0.005	0.006	0.012	0.016	0.015
	AVERAGE	0.105	0.101	0.143	0.104	0.107	0.111	0.082	0.184	0.099
	SUM	0.210	0.203	0.286	0.209	0.215	0.222	0.164	0.368	0.199
5 HOURS T_1	REPLICATE 1	0.109	0.112	0.156	0.151	0.116	0.120	0.105	0.176	0.128
	REPLICATE 2	0.122	0.114	0.148	0.146	0.118	0.118	0.112	0.216	0.116
	RANGE	0.013	0.002	0.008	0.005	0.002	0.002	0.007	0.040	0.012
	AVERAGE	0.115	0.113	0.152	0.148	0.117	0.119	0.108	0.196	0.122
	SUM	0.231	0.226	0.304	0.297	0.234	0.238	0.217	0.392	0.244
28 HOURS T_2	REPLICATE 1	0.132	0.122	0.178	0.176	0.170	0.150	0.110	0.216	0.166
	REPLICATE 2	0.134	0.140	0.176	0.154	0.144	0.148	0.127	0.232	0.141
	RANGE	0.002	0.018	0.002	0.022	0.026	0.002	0.017	0.016	0.025
	AVERAGE	0.133	0.131	0.177	0.165	0.157	0.149	0.118	0.224	0.153
	SUM	0.266	0.262	0.354	0.330	0.314	0.298	0.237	0.448	0.307

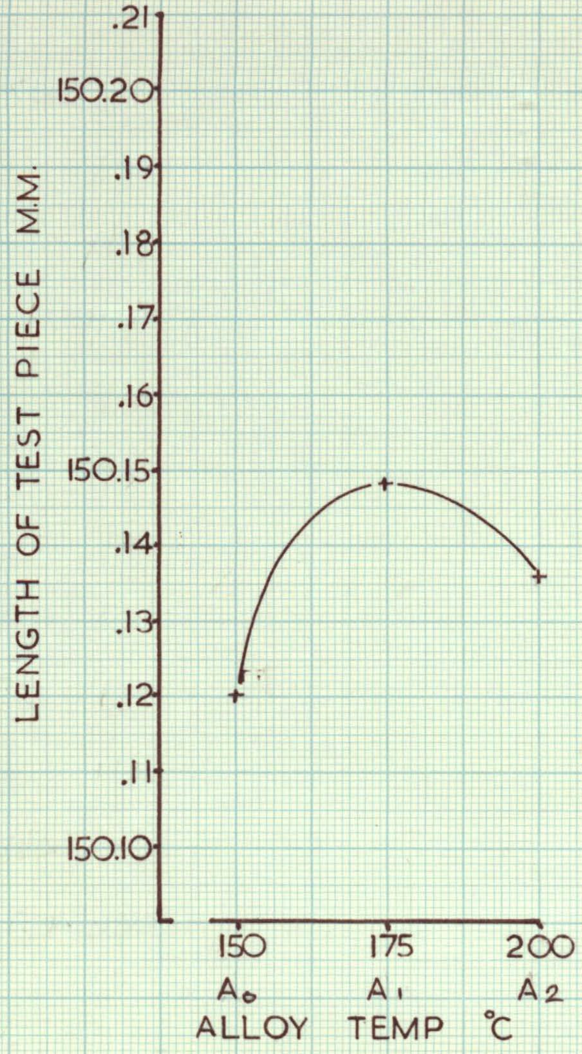


FIGURE 31

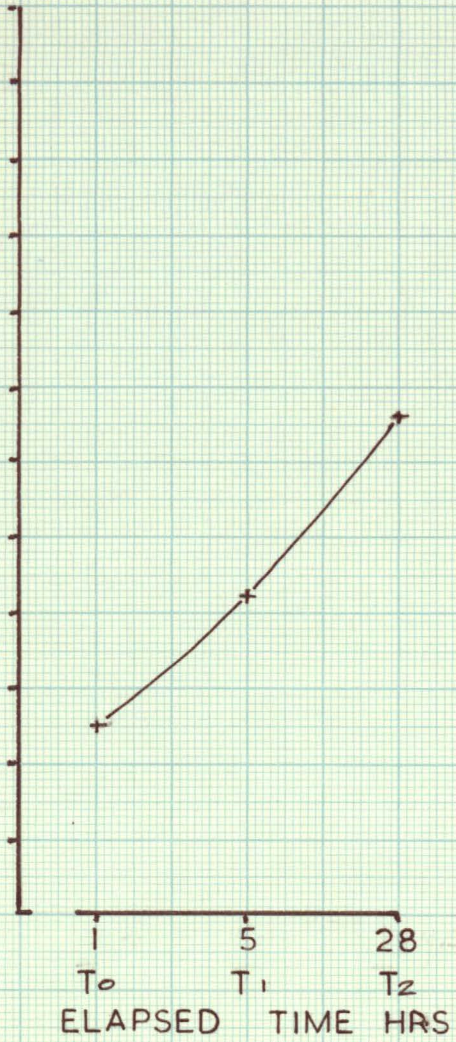


FIGURE 32

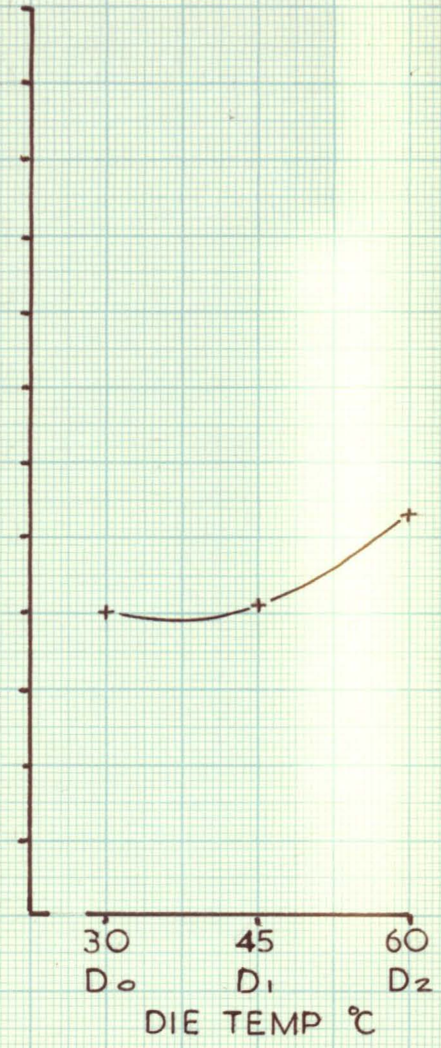


FIGURE 33

FIGURE 34

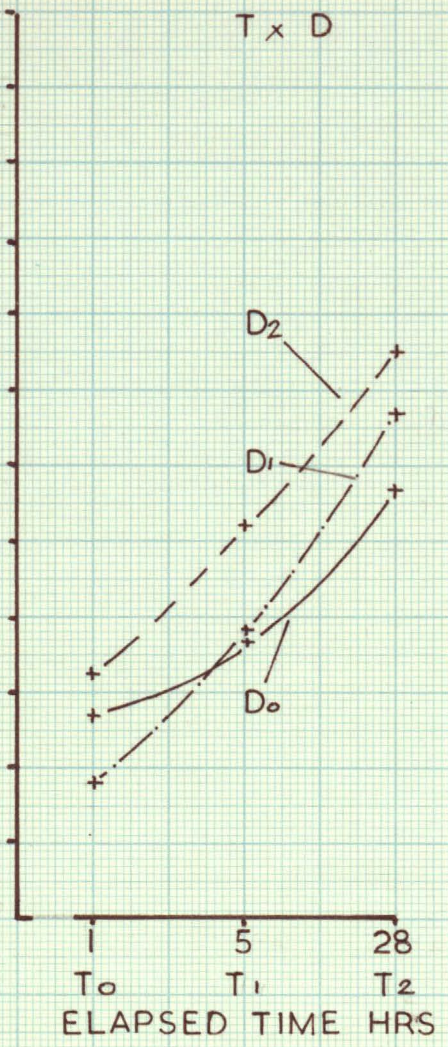


FIGURE 35

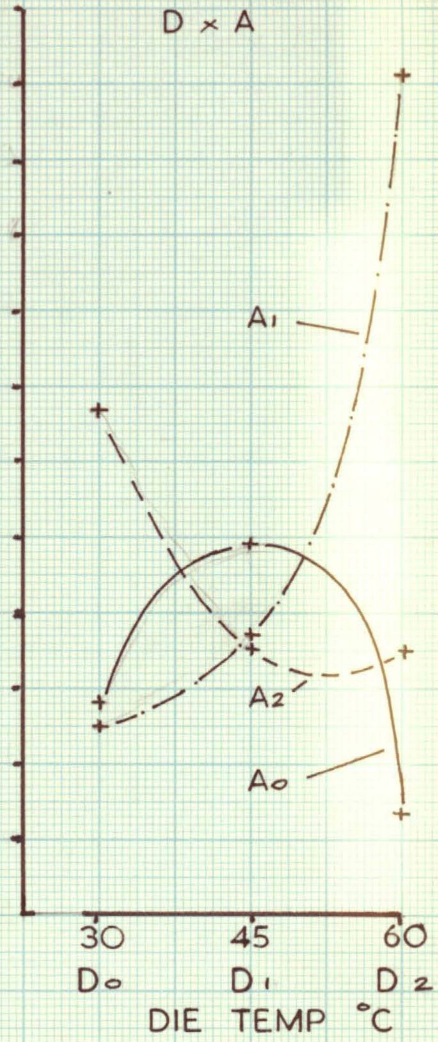


FIGURE 36

3.7.4 Significance of Results

3.7.4.1 Length change v alloy casting temperature - Figure 31

Statistical significance of results - greater than 99%.

Cerrotru castings poured at 175°C grew dimensionally more than castings poured at either 150°C or 200°C. Even allowing for the increased die length associated with the higher die temperature at solidification, there is still a 'peak' in length change.

3.7.4.2 Length change v time after casting - Figure 32

Statistical significance of results - greater than 99%.

Cerrotru grows after solidification; 28 hours after casting, the test piece was .041mm longer than at 1 hour after casting. This represents a growth of 0.027%.

3.7.4.3 Length change v die temperature - Figure 33

Statistical significance of results - greater than 99%.

The slightly higher growth rate associated with higher die temperatures is partly explained by the die expanding at the higher temperature. Reference to Figure 24 confirms this.

3.7.4.4 Interaction between alloy casting temperature and time after casting - Figure 34

Statistical significance of results - N.S.

There was no significant interaction. Changes in pour temperature do not affect the rate of dimensional change associated with time.

3.7.4.5 Interaction between time after casting and die temperature - Figure 35

Statistical significance of results - N.S.

There was no significant interaction. The effect of elapsed time is increase in length and this is not affected by change in die temperature.

3.7.4.6 Interaction between die temperature and alloy casting temperature - Figure 36

Statistical significance of results - greater than 99%.

There is a very strong interaction. The complex interaction indicates how the choice of die temperature should not be made without reference to alloy casting temperature.

3.8.

3.8.1. ALLOY:- Cerrotru TEST:- Holding force kg.		DIE TEMPERATURE °C								
		30 D_0			45 D_1			60 D_2		
TIME AFTER CASTING		ALLOY TEMP. °C			ALLOY TEMP. °C			ALLOY TEMP. °C		
		150 A_0	175 A_1	200 A_2	150 A_0	175 A_1	200 A_2	150 A_0	175 A_1	200 A_2
1 HOUR T_0	REPLICATE 1	1.00*	0.10*	0.00*	1.00*	18.00	12.00	12.00	24.00	0.50*
	REPLICATE 2	11.50		0.00*	0.25*					
	RANGE									
	AVERAGE	6.25	0.10	0.00	0.62	18.00	12.00	12.00	24.00	0.50
	SUM									
5 HOURS T_1	REPLICATE 1	1.00		8.00					2.00*	20.00
	REPLICATE 2		0.50*		1.00	0.00*	0.00*	0.50*	0.00*	0.50*
	RANGE									
	AVERAGE	1.00	0.50	8.00	1.00	0.00	0.00	0.50	1.00	10.25
	SUM									
28 HOURS T_2	REPLICATE 1		1.00		4.50	0.00*	0.50*	0.00*		
	REPLICATE 2	0.00*	8.50	5.00		5.50	6.50	4.20	3.00	6.50
	RANGE									
	AVERAGE	0.00	4.75	5.00	4.50	2.75	3.50	2.10	3.00	6.50
	SUM									

* Denotes pin at temperature gauge end of die.

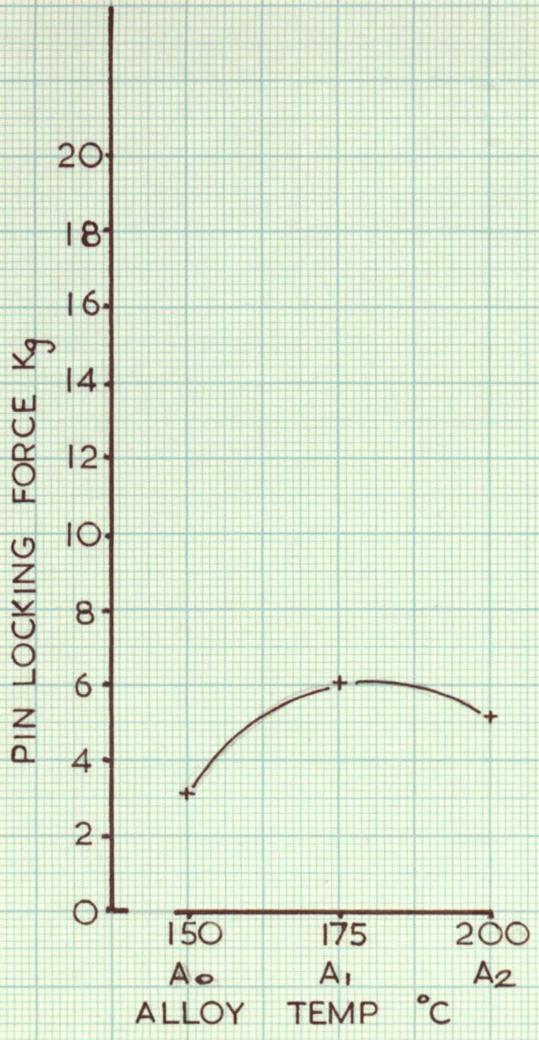


FIGURE 37

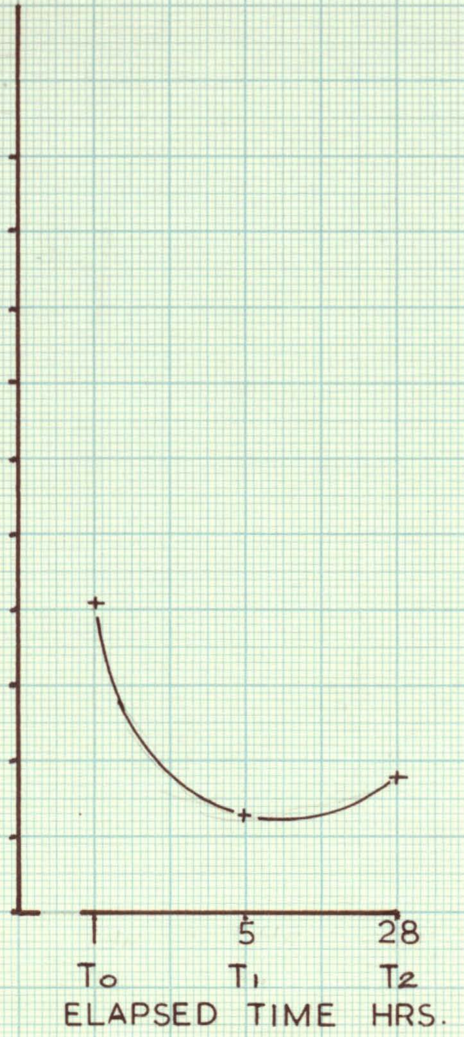


FIGURE 38

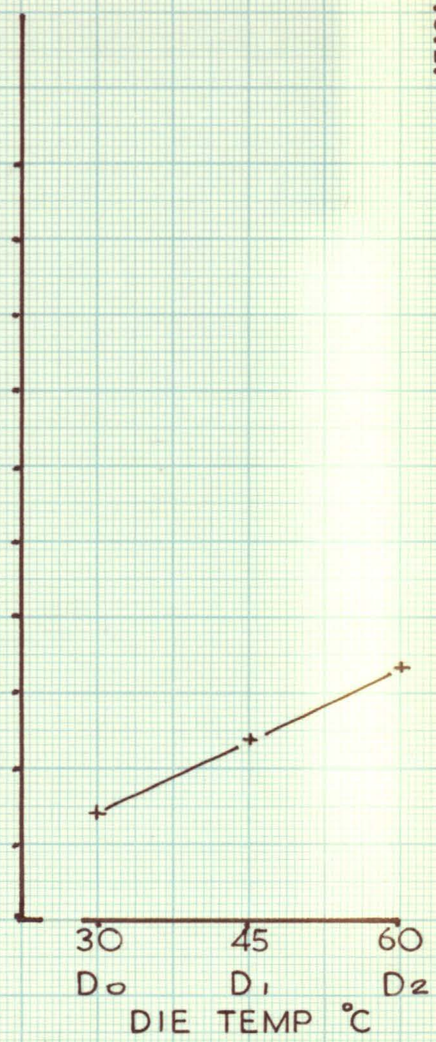


FIGURE 39

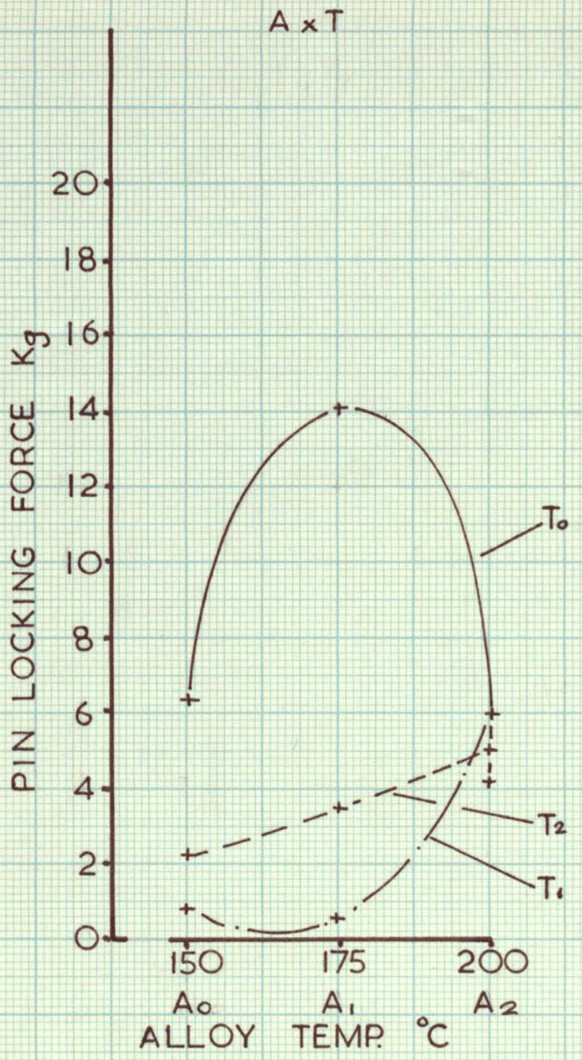


FIGURE 40

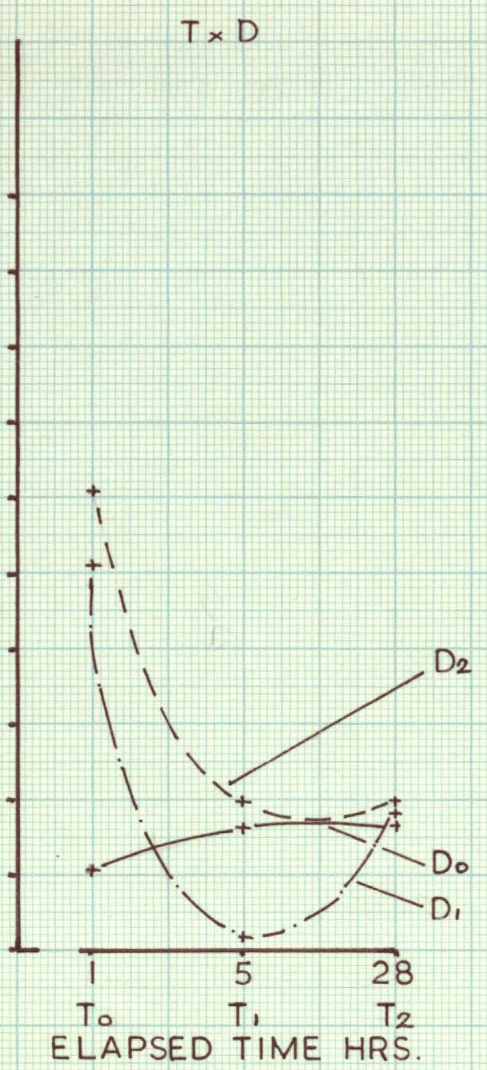


FIGURE 41

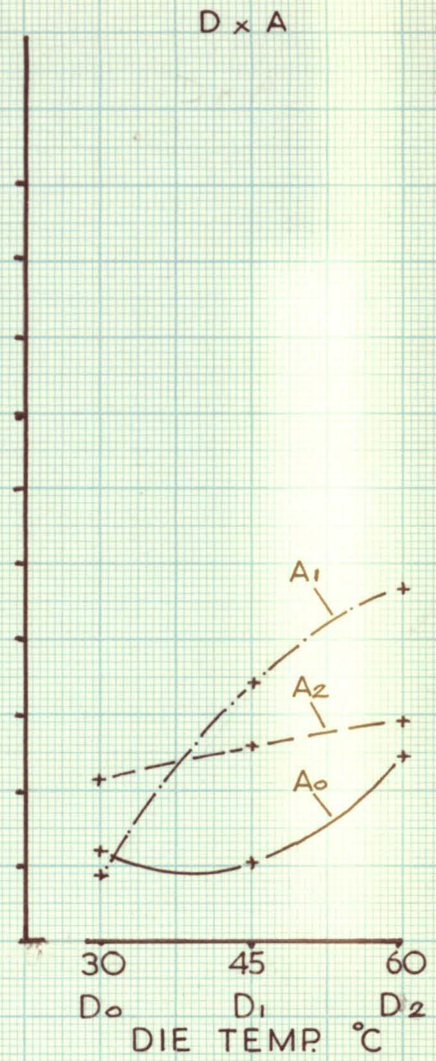


FIGURE 42

3.8.4 Significance of Results

Cerrotru holding force - Figure 37, 38, 39, 40, 41 and 42

Statistical significance of results - N.S.

The results obtained, being statistically not significant, represent an experimental failure. The experiment was not replicated and better results may be obtained if this is done. The statistical assumption of normal distribution needs re-examination. Some of the results suggest that a double peaked distribution may be more appropriate. The first peak representing the pins which were held in the block by friction only, and the second peak representing the pins where there was a metallurgical bond. This is of course, only supposition, but more extensive testing could be undertaken to investigate this possibility.

The average holding force for all the Cerrotru holding force tests was 4.7Kg.

3.9.

3.9.1. ALLOY:- Cerrocast TEST:- Hardness Rockwell 'L' scale		DIE TEMPERATURE °C								
		30 D_0			45 D_1			60 D_2		
TIME AFTER CASTING		ALLOY TEMP. °C			ALLOY TEMP. °C			ALLOY. TEMP. °C		
		175 A_0	200 A_1	225 A_2	175 A_0	200 A_1	225 A_2	175 A_0	200 A_1	225 A_2
1 HOUR T_0	REPLICATE 1	76.12	77.78	79.10	80.18	74.34	80.60	79.82	77.64	80.60
	REPLICATE 2	76.16	78.64	75.52	78.54	75.66	81.12	78.60	80.90	79.80
	RANGE	0.04	0.86	3.58	1.64	1.32	0.52	1.22	3.26	0.80
	AVERAGE	76.14	78.21	77.31	79.36	75.00	80.86	79.21	79.27	80.20
	SUM	152.28	156.42	154.62	158.72	150.00	161.72	158.42	158.54	160.40
5 HOURS T_1	REPLICATE 1	75.38	76.78	81.80	78.68	76.94	80.18	78.08	77.80	80.68
	REPLICATE 2	77.60	78.06	78.94	79.80	77.84	83.52	78.30	81.72	80.10
	RANGE	2.22	1.28	2.86	1.12	0.90	3.34	0.22	3.92	0.58
	AVERAGE	76.49	77.42	80.37	79.24	77.39	81.85	78.19	79.76	80.39
	SUM	152.98	154.84	160.74	158.48	154.78	163.70	156.38	159.52	160.78
28 HOURS T_2	REPLICATE 1	76.20	78.10	81.40	78.48	75.40	80.22	77.58	76.90	80.00
	REPLICATE 2	77.70	78.66	77.76	78.36	77.16	83.38	76.84	79.82	78.82
	RANGE	1.50	0.56	3.64	0.12	1.76	3.16	0.74	2.92	1.18
	AVERAGE	76.95	78.38	79.58	78.42	76.28	81.80	77.21	78.36	79.41
	SUM	153.90	156.76	159.16	156.84	152.56	163.60	154.42	156.72	158.82

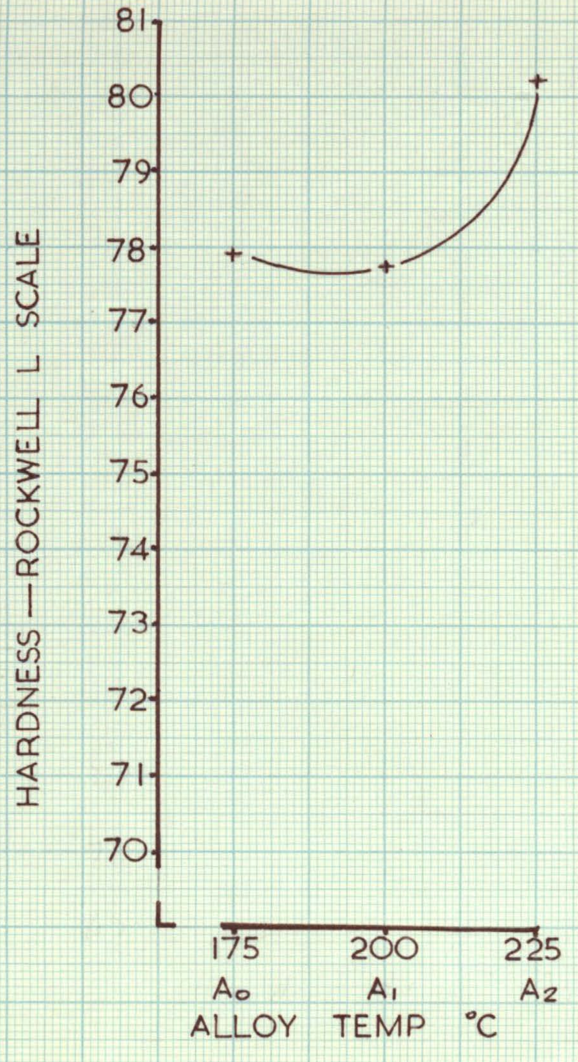


FIGURE 43

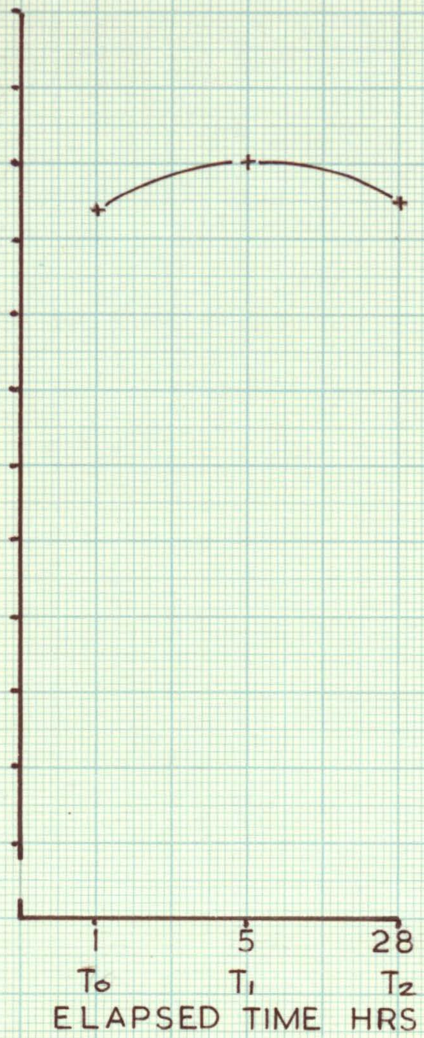


FIGURE 44

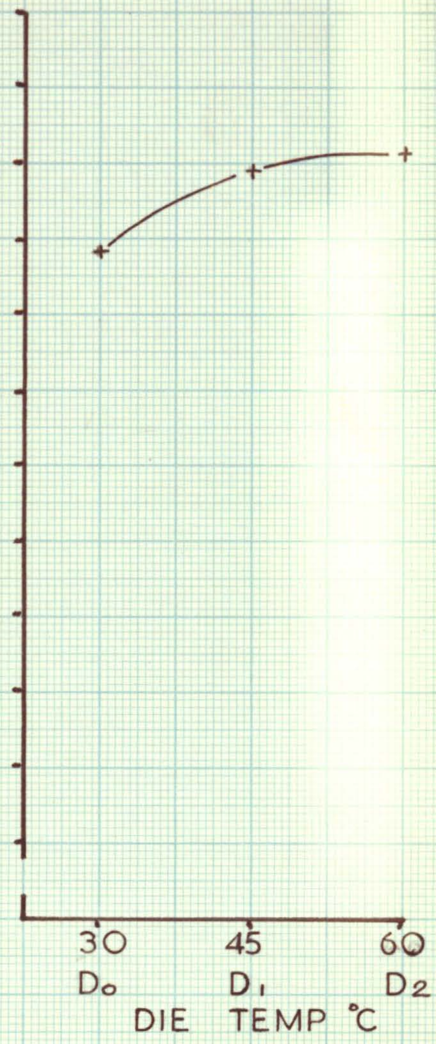


FIGURE 45

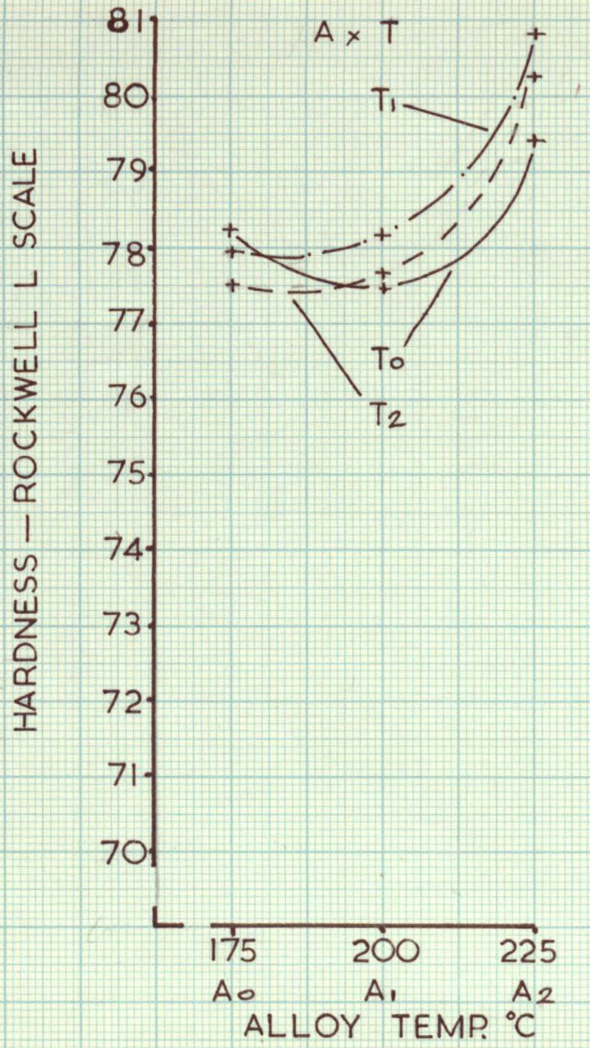


FIGURE 46

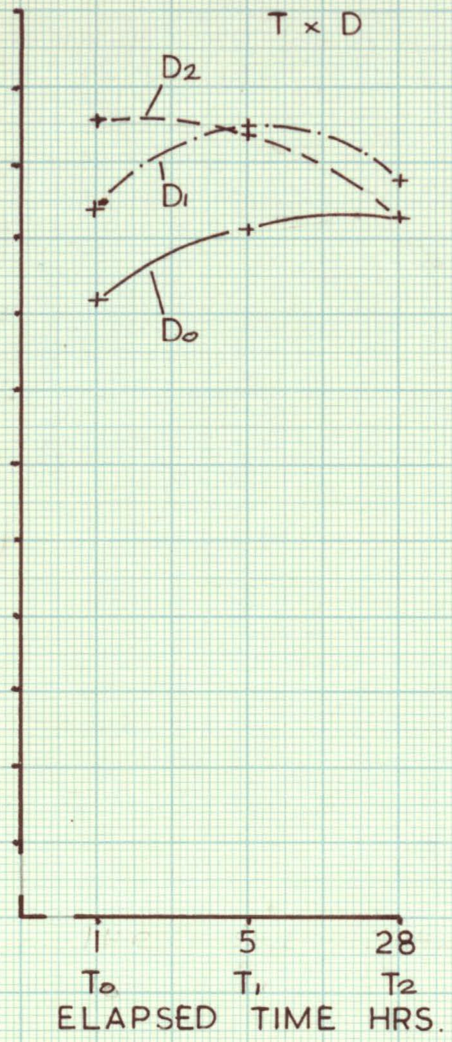


FIGURE 47

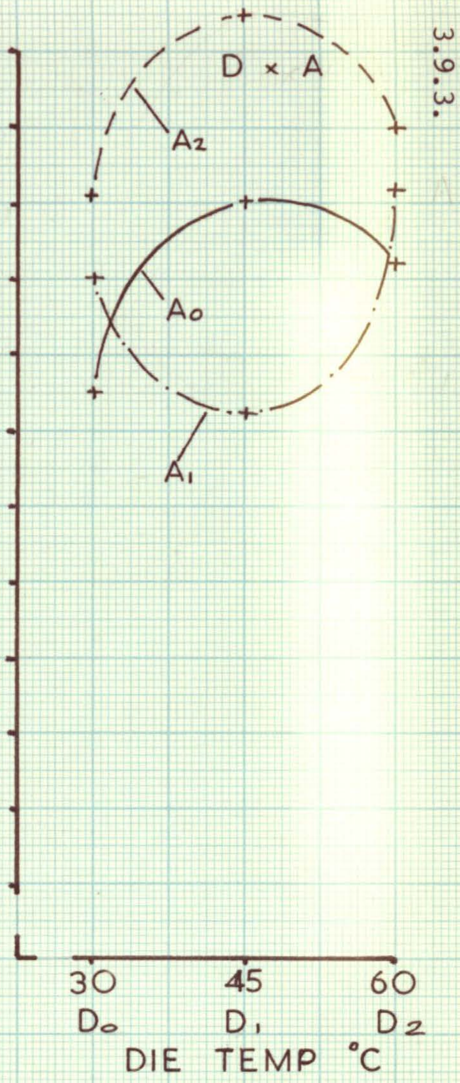


FIGURE 48

3.9.4 Significance of Results

3.9.4.1 Hardness v Alloy Casting Temperature - Figure 43

Statistical significance of results - greater than 99%.

The cerrocast was harder, Rockwell 'L' scale 80, at the highest alloy pouring temperature. The lowest hardness was at a pour temperature of approximately 190°C.

3.9.4.2 Hardness v Time after Casting - Figure 44

Statistical significance of results - N.S.

The hardness remained constant between 78 and 79 Rockwell 'L' scale between 1 hour and 28 hours after casting.

3.9.4.3 Hardness v Die Temperature at Cast - Figure 45

Statistical significance of results - greater than 95%.

There was a small but significant increase in hardness as the die temperature increased.

3.9.4.4 Interaction between alloy casting temperature and time after casting - Figure 46

There is no significant interaction.

3.9.4.5 Interaction between time after casting and die temperature - Figure 47

There is no significant interaction.

3.9.4.6 Interaction between die temperature and alloy casting temperature - Figure 48

Statistical significance of results - greater than 99%.

There is a very strong interaction with the die temperature of 45°C giving both the highest and lowest hardness figures dependent upon the alloy temperature. An alloy temperature of 200°C gave a hardness of 76 Rockwell 'L' scale whilst an alloy temperature of 225°C gave a hardness of 81.5 Rockwell 'L' scale.

3.10.

3.10.1. ALLOY:- Cerrocast TEST:- Length change mm 150mm +		DIE TEMPERATURE °C								
		30 D_0			45 D_1			60 D_2		
TIME AFTER CASTING		ALLOY TEMP. °C			ALLOY TEMP. °C			ALLOY TEMP. °C		
		175 A_0	200 A_1	225 A_2	175 A_0	200 A_1	225 A_2	175 A_0	200 A_1	225 A_2
1 HOUR T_0	REPLICATE 1	0.184	0.184	0.214	0.138	0.176	0.193	0.160	0.226	0.168
	REPLICATE 2	0.170	0.166	0.208	0.132	0.168	0.194	0.172	0.204	0.188
	RANGE	0.014	0.018	0.006	0.006	0.008	0.001	0.012	0.022	0.020
	AVERAGE	0.177	0.175	0.211	0.135	0.172	0.193	0.166	0.215	0.178
	SUM	0.354	0.350	0.422	0.270	0.344	0.387	0.332	0.430	0.356
5 HOURS T_1	REPLICATE 1	0.200	0.212	0.214	0.182	0.206	0.215	0.182	0.225	0.192
	REPLICATE 2	0.206	0.206	0.212	0.150	0.188	0.205	0.182	0.224	0.190
	RANGE	0.006	0.006	0.002	0.032	0.018	0.010	0.000	0.001	0.002
	AVERAGE	0.203	0.204	0.213	0.166	0.147	0.210	0.182	0.224	0.191
	SUM	0.406	0.418	0.426	0.332	0.394	0.420	0.364	0.449	0.382
28 HOURS T_2	REPLICATE 1	0.242	0.242	0.238	0.194	0.230	0.236	0.218	0.264	0.232
	REPLICATE 2	0.238	0.224	0.230	0.206	0.206	0.230	0.228	0.246	0.230
	RANGE	0.004	0.018	0.008	0.012	0.024	0.006	0.010	0.018	0.002
	AVERAGE	0.240	0.233	0.234	0.200	0.218	0.233	0.223	0.255	0.231
	SUM	0.480	0.466	0.468	0.400	0.436	0.466	0.446	0.510	0.462

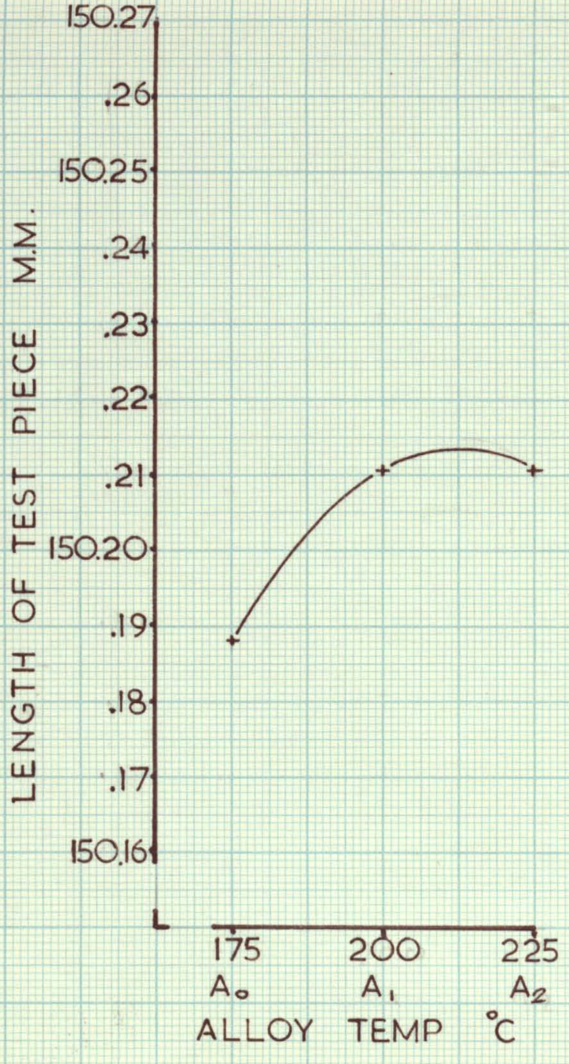


FIGURE 49

FIGURE 50

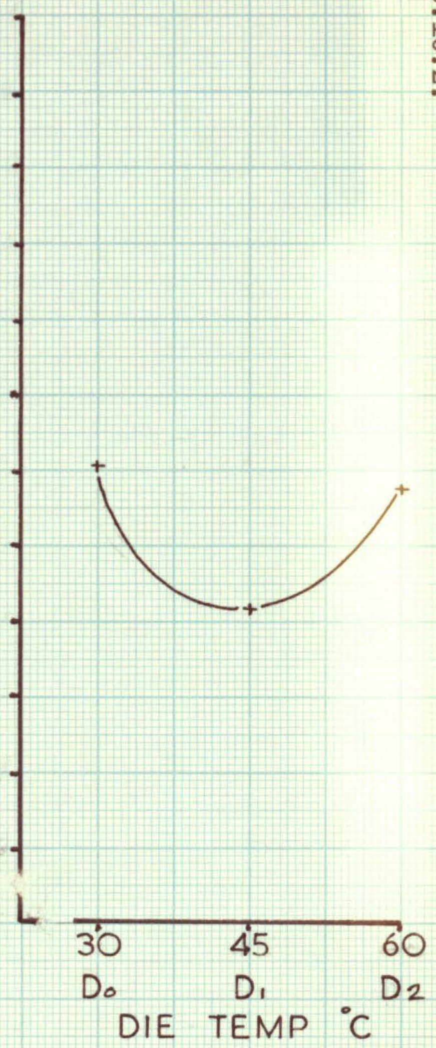


FIGURE 51

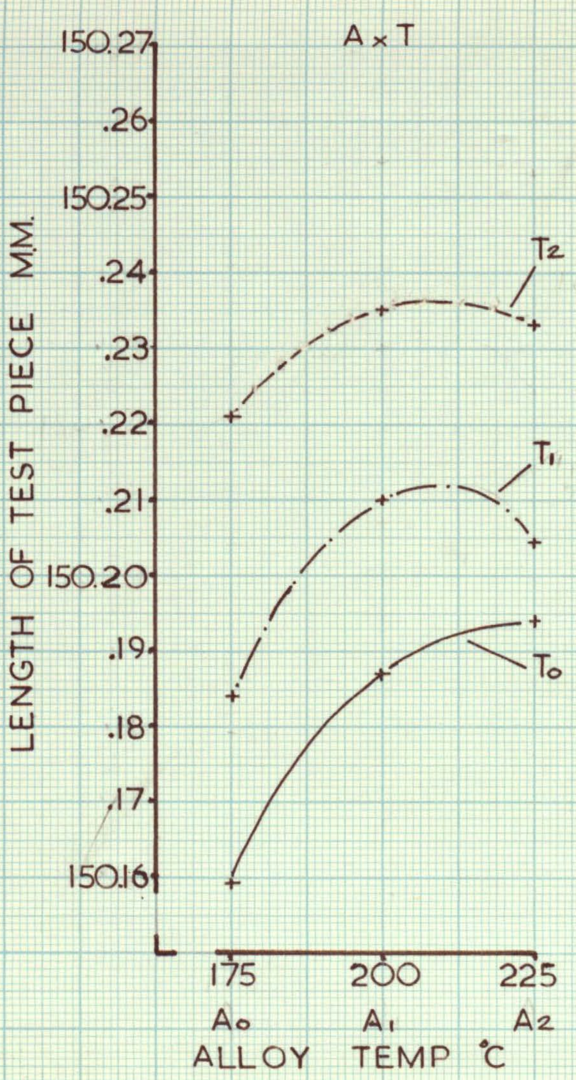


FIGURE 52

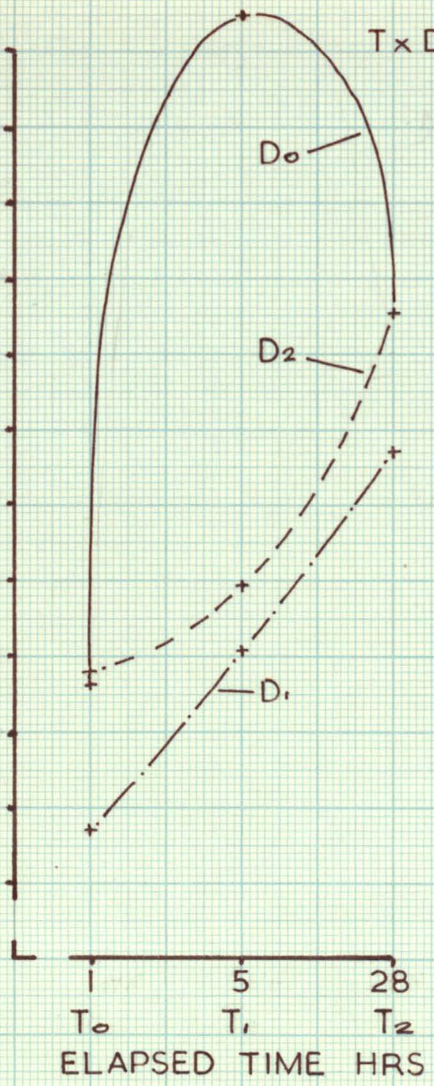


FIGURE 53

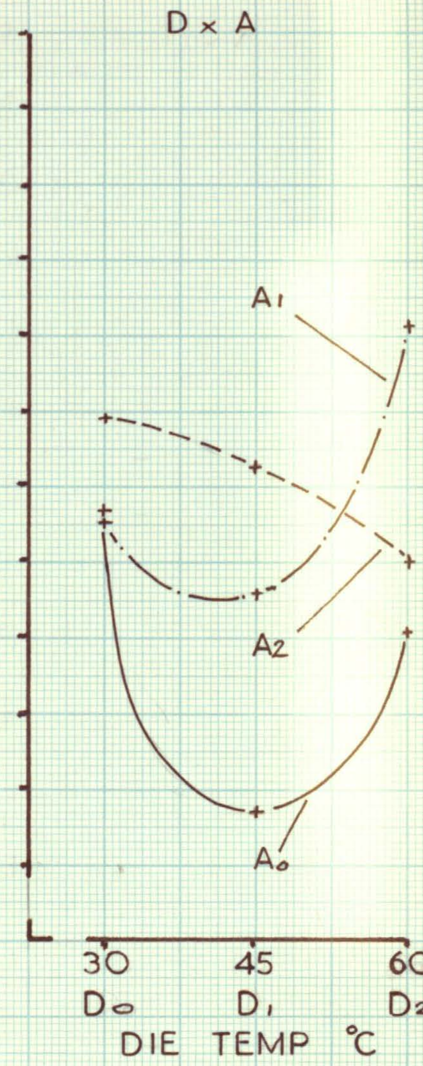


FIGURE 54

3.10.4 Significance of Results

3.10.4.1 Length change v Alloy Casting Temperature - Figure 49

Statistical significance of results - greater than 99%.

The growth of the Cerrocast was significantly higher when the alloy was cast at the higher temperature.

3.10.4.2 Length change v Time after Casting - Figure 50

Statistical significance of results - greater than 99%.

There was a growth in the Cerrocast of 0.04mm between 1 hour and 28 hours after casting. This represents a growth of 0.04%.

3.10.4.3 Length change v Die Temperature - Figure 51

Statistical significance of results - greater than 99%.

Growth was at its lowest at a die temperature of 45°C.

3.10.4.4 Interaction between Alloy Casting Temperature and Time after Casting - Figure 52

There is no statistical interaction.

3.10.4.5 Interaction between Time after Casting and Die Temperature - Figure 53

There is no statistical interaction.

3.10.4.6 Interaction between Die Temperature and Alloy Casting Temperature - Figure 54

Statistical significance of results - greater than

97.5%.

There is a strong interaction. The castings poured at 175°C and 200°C into a die at 45°C gave lower dimensional growth than with the die temperature at 30°C and 60°C. The alloy poured at 225°C however, gave minimum growth when cast into a die at 60°C.

3.11.

3.11.1. ALLOY:- Cerrocast TEST:- Holding force kg.		DIE TEMPERATURE °C								
		30 D_o			45 D_1			60 D_2		
TIME AFTER CASTING		ALLOY TEMP. °C			ALLOY TEMP. °C			ALLOY TEMP. °C		
		175 A_o	200 A_1	225 A_2	175 A_o	200 A_1	225 A_2	175 A_o	200 A_1	225 A_2
1 HOUR T_o	REPLICATE 1	16.50*	20.00*	16.00*	16.50	20.00	24.50	19.25*	16.50	11.00*
	REPLICATE 2	8.50*	15				10			
	RANGE									
	AVERAGE	12.50	17.50	16.00	16.50	20.00	17.25	19.25	16.50	11.00
	SUM									
5 HOURS T_1'	REPLICATE 1				14.20*		33.50*		10.50*	6.50
	REPLICATE 2	11.00	17.00	5.50	18.00	12.50		11.50	9.00	17.00*
	RANGE									
	AVERAGE	11.00	17.00	5.50	16.10	12.50	33.50	11.50	9.75	11.75
	SUM									
28 HOURS T_2'	REPLICATE 1	4.00	12.00	2.00		3.50*		3.50		
	REPLICATE 2		7.00*	11.00*	15.00*	6.00*	13.00*	5.00*	10.00*	17.00
	RANGE									
	AVERAGE	4.00	9.50	6.50	15.00	4.75	13.00	4.25	10.00	17.00

* Denotes pin at temperature gauge end of die.

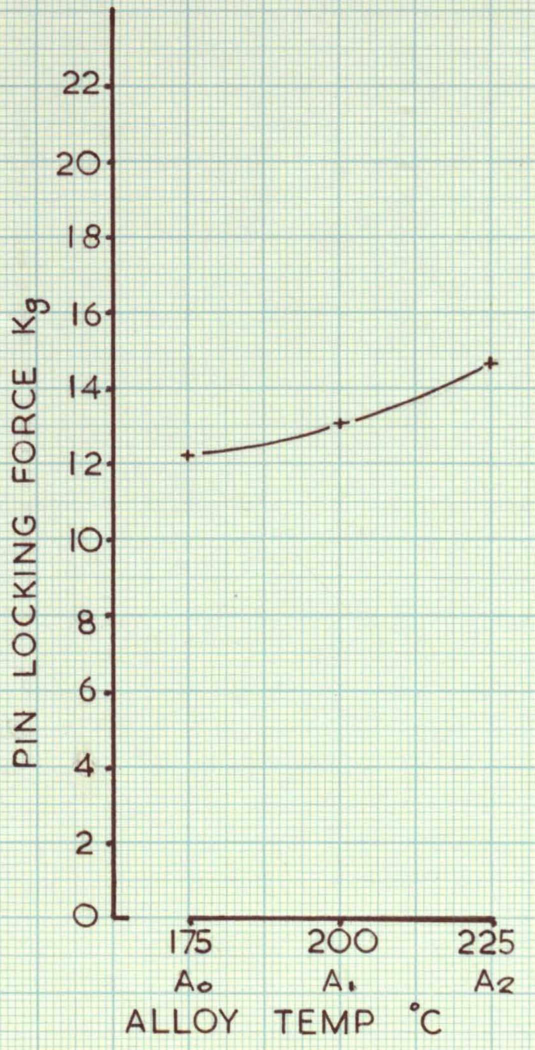


FIGURE 55

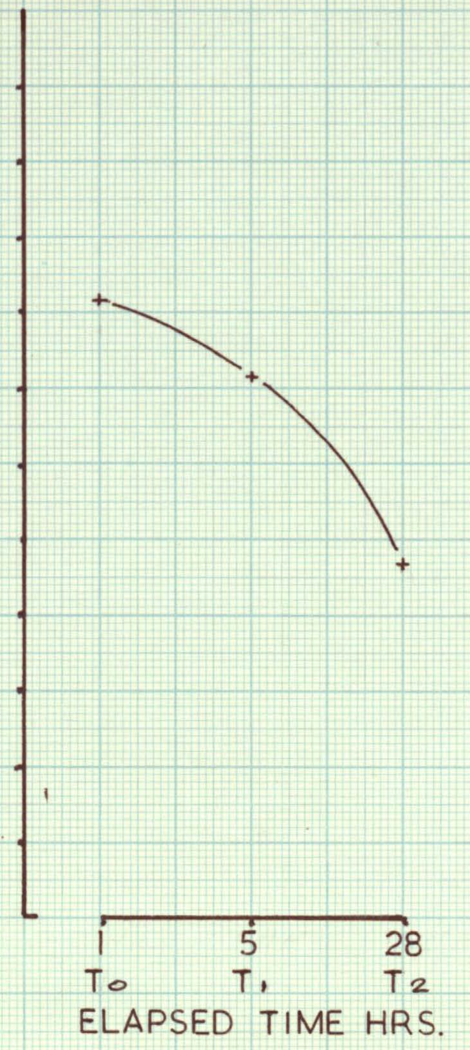


FIGURE 56

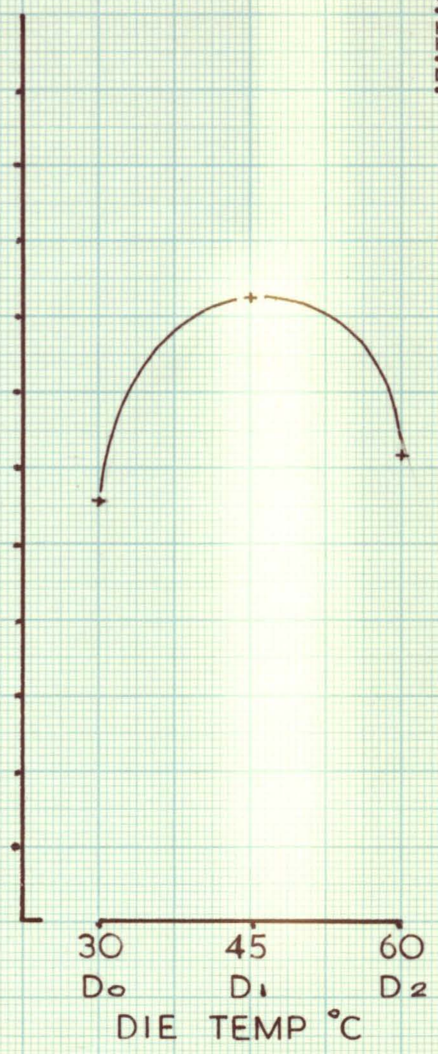


FIGURE 57

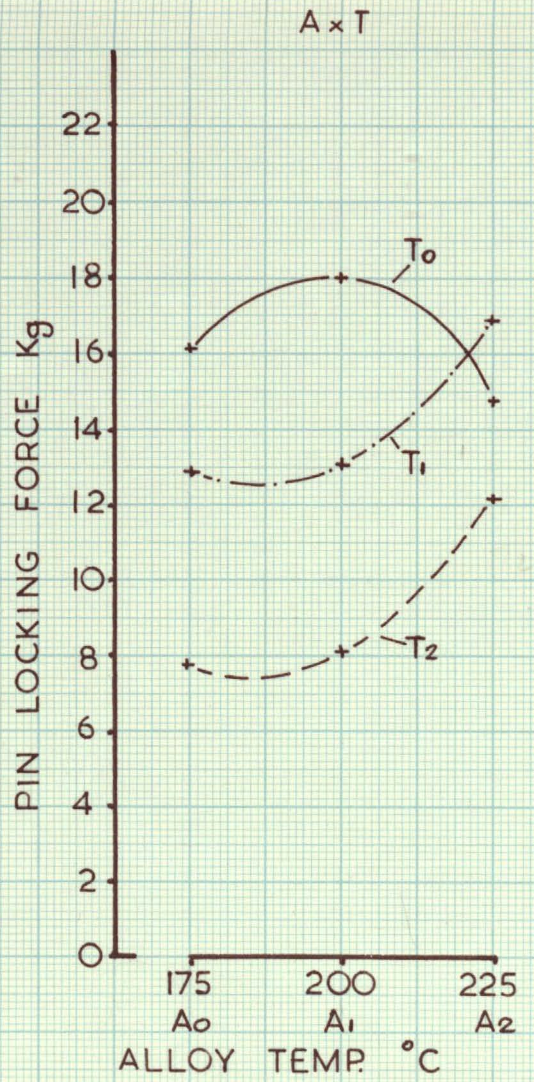


FIGURE 58

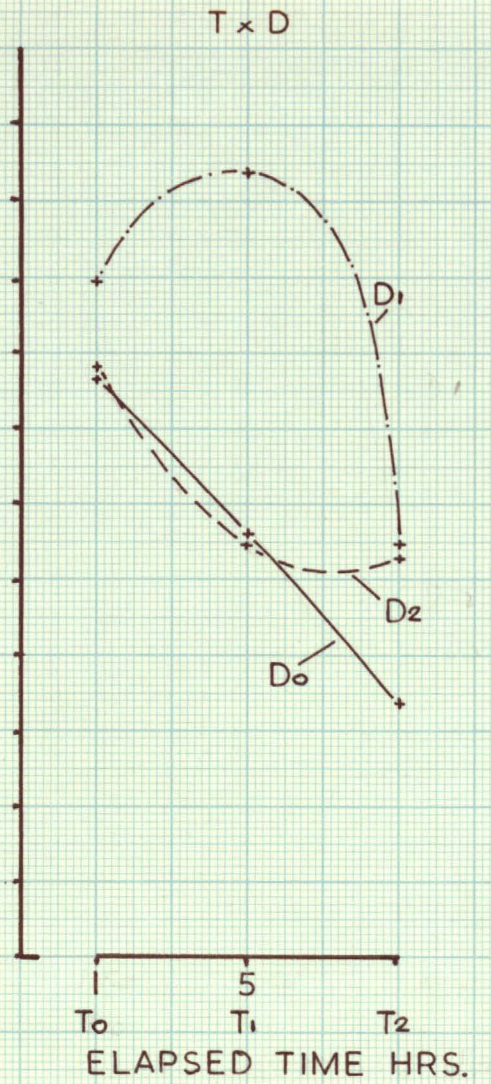


FIGURE 59

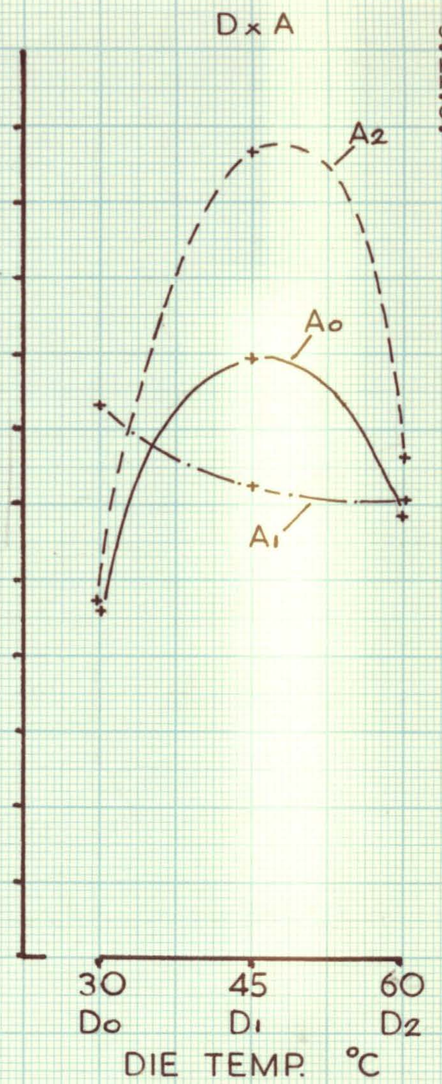


FIGURE 60

3.11.4 Significance of Results

Cerrocast holding force - Figures 55,56,57,58 59 and 60

Statistical significance of results - N.S.

The results obtained, being statistically not significant, represent an experimental failure. The experiment was not replicated and better results may be obtained if this is done. The statistical assumption of normal distribution needs re-examination. Some of the results suggest that a double peaked distribution may be more appropriate. The first peak representing the pins which were held in the block by friction only, and the second peak representing the pins where there was a metallurgical bond. This is of course, only supposition, but more extensive testing could be undertaken to investigate this possibility.

The average holding force for all the Cerrocast holding force test was 13Kg.

3.12.

3.12.1. ALLOY:- Frycap 7 TEST:- Hardness Rockwell 'L' scale		DIE TEMPERATURE ^{o}C								
		30 D_o			45 D_1			60 D_2		
TIME AFTER CASTING		ALLOY TEMP. ^{o}C			ALLOY TEMP. ^{o}C			ALLOY TEMP. ^{o}C		
		250 A_o	275 A_1	300 A_2	250 A_o	275 A_1	300 A_2	250 A_o	275 A_1	300 A_2
1 HOUR T_o	REPLICATE 1	75.42	77.42	77.52	72.56	74.20	77.54	72.54	74.30	76.42
	REPLICATE 2	74.52	77.92	75.12	74.22	74.50	77.88	72.10	74.72	73.98
	RANGE	0.90	0.50	2.40	1.66	0.30	0.34	0.44	0.42	2.44
	AVERAGE	74.97	77.67	76.32	73.39	74.35	77.71	72.32	74.51	75.20
	SUM	149.94	155.34	152.64	146.78	148.70	155.42	144.64	149.02	150.40
5 HOURS T_1	REPLICATE 1	76.30	77.86	76.32	73.54	74.66	78.12	72.12	75.14	77.88
	REPLICATE 2	75.30	75.70	77.68	73.70	74.62	78.92	73.76	74.92	74.68
	RANGE	1.00	2.16	1.36	0.16	0.04	0.80	1.64	0.22	3.20
	AVERAGE	75.80	76.78	77.00	73.62	74.64	78.52	72.94	75.03	76.28
	SUM	151.60	153.56	154.00	147.24	149.28	157.04	145.88	150.06	152.56
28 HOURS T_2	REPLICATE 1	73.80	76.70	75.86	73.40	74.84	77.66	75.32	73.34	75.50
	REPLICATE 2	74.10	74.76	75.90	74.12	74.58	77.54	73.10	74.08	74.48
	RANGE	0.30	1.94	0.04	0.72	0.26	0.12	2.22	0.74	1.02
	AVERAGE	73.95	75.73	75.89	73.76	74.71	77.60	74.16	73.71	74.99
	SUM	147.90	151.46	151.76	147.52	149.42	155.20	148.42	147.42	149.98

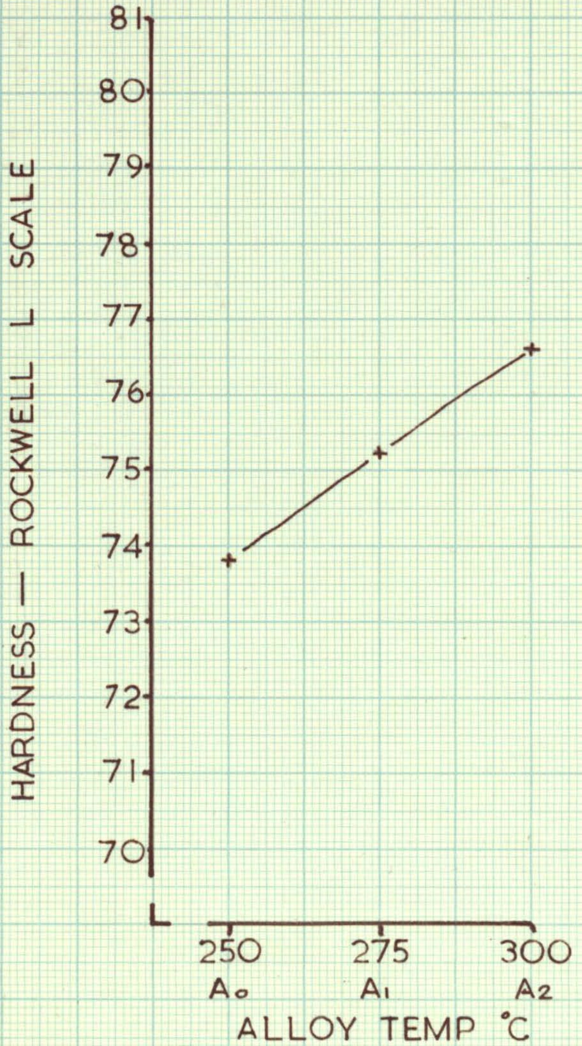


FIGURE 61

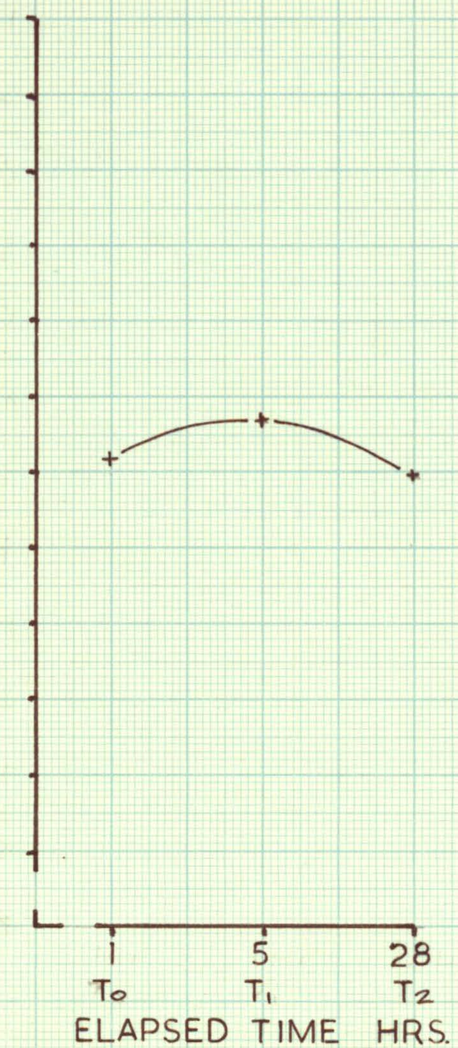


FIGURE 62

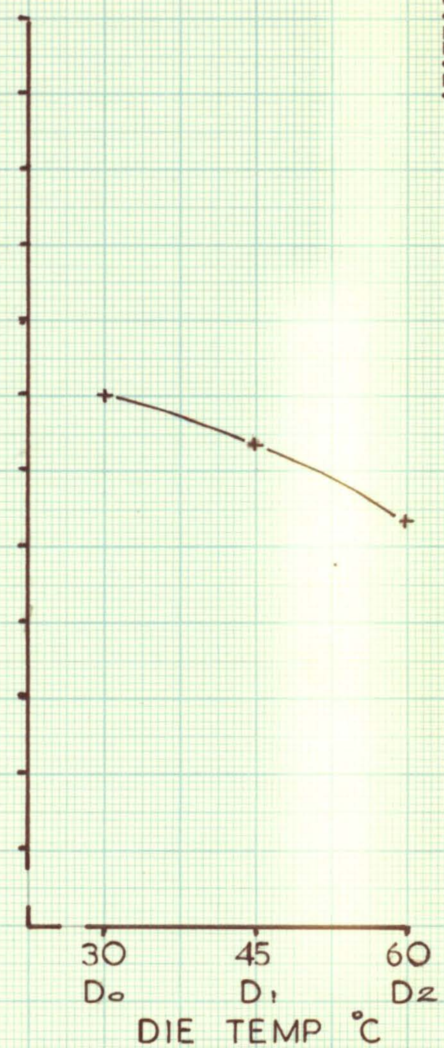


FIGURE 63

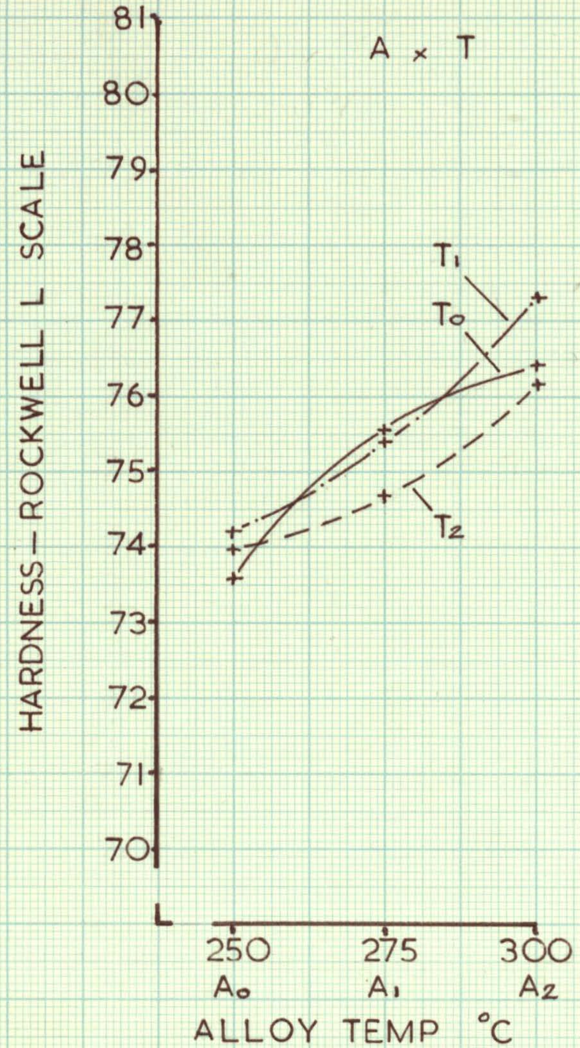


FIGURE 64

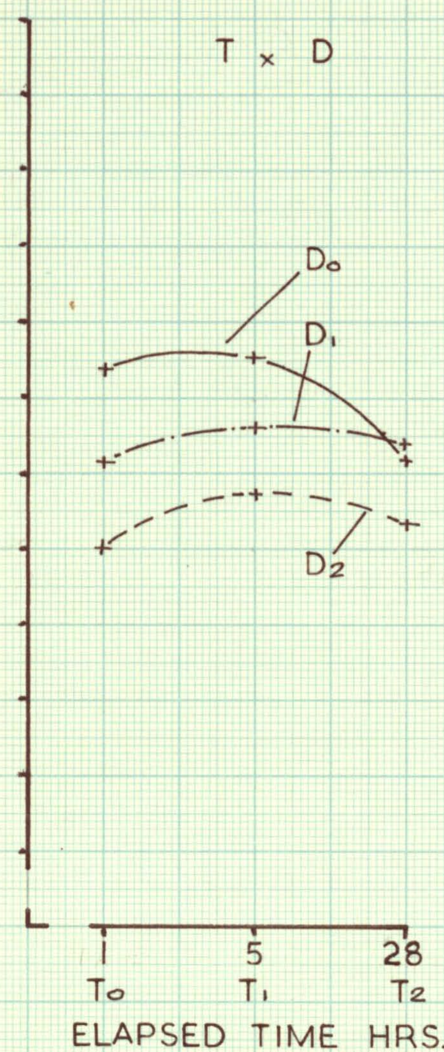


FIGURE 65

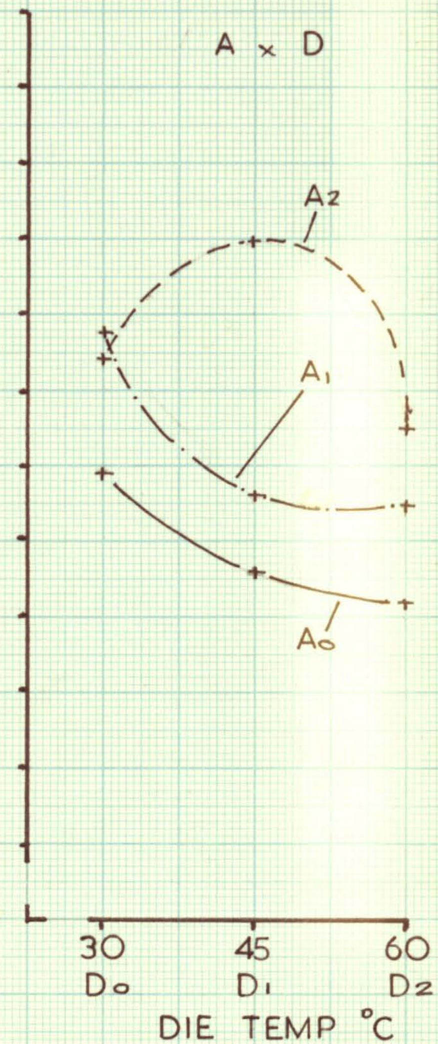


FIGURE 66

3.12.4 Significance of Results

3.12.4.1 Hardness v Alloy Casting Temperature - Figure 61

Statistical significance of results - greater than 99%.

Increasing the pour temperature of Frycap 7 alloy from 250°C to 300°C resulted in significantly harder castings.

3.12.4.2 Hardness v Time after Casting - Figure 62

Statistical significance of results - N.S.

There was no significant change in dimension of the Frycap 7 test piece between 1 hour and 28 hours after casting.

3.12.4.3 Hardness v Die Temperature - Figure 63

Statistical significance of results - greater than 99%.

Reducing the die temperature from 60°C to 30°C gave significantly harder Frycap 7 castings.

3.12.4.4 Interaction between Alloy Casting Temperature and Time after Casting - Figure 64

There is no statistical interaction.

3.12.4.5 Interaction between Time after Casting and Die Temperature - Figure 65

There is no statistical interaction.

3.12.4.6 Interaction between Die Temperature and Alloy Temperature - Figure 66

Statistical significance of results - greater than 99%.

There is a very strong interaction between the Frycap 7 pouring temperature and the die temperature. The hardest casting resulted when alloy at 300°C was poured into the die at 45°C. For pour temperature of 275°C, the hardest castings resulted when the 30°C die was used.

3.13.

3.13.1. ALLOY:- Frycap 7		DIE TEMPERATURE °C								
TEST:- Length change mm. 149 mm +		30 D_o			45 D_1			60 D_2		
TIME AFTER CASTING		ALLOY TEMP. °C			ALLOY TEMP. °C			ALLOY TEMP. °C		
		250 A_o	275 A_1	300 A_2	250 A_o	275 A_1	300 A_2	250 A_o	275 A_1	300 A_2
1 HOUR T_o	REPLICATE 1	0.206	0.220	0.252	0.242	0.246	0.280	0.300	0.284	0.282
	REPLICATE 2	0.208	0.248	0.242	0.244	0.256	0.260	0.286	0.268	0.304
	RANGE	0.002	0.028	0.010	0.002	0.010	0.020	0.014	0.016	0.022
	AVERAGE	0.207	0.234	0.247	0.243	0.251	0.270	0.293	0.276	0.293
	SUM	0.414	0.468	0.494	0.486	0.502	0.540	0.586	0.552	0.586
5 HOURS T_1	REPLICATE 1	0.198	0.220	0.250	0.190	0.284	0.270	0.268	0.262	0.286
	REPLICATE 2	0.192	0.240	0.250	0.222	0.286	0.250	0.274	0.294	0.304
	RANGE	0.006	0.020	0.000	0.032	0.002	0.020	0.006	0.032	0.018
	AVERAGE	0.195	0.230	0.250	0.206	0.285	0.260	0.271	0.278	0.295
	SUM	0.390	0.460	0.500	0.412	0.570	0.520	0.542	0.556	0.590
28 HOURS T_2	REPLICATE 1	0.200	0.236	0.222	0.222	0.270	0.256	0.270	0.270	0.296
	REPLICATE 2	0.200	0.238	0.248	0.206	0.294	0.298	0.254	0.280	0.280
	RANGE	0.000	0.002	0.026	0.016	0.024	0.042	0.016	0.010	0.016
	AVERAGE	0.200	0.237	0.235	0.219	0.282	0.277	0.262	0.275	0.288
	SUM	0.400	0.474	0.470	0.428	0.564	0.554	0.524	0.550	0.576

3.13.2.

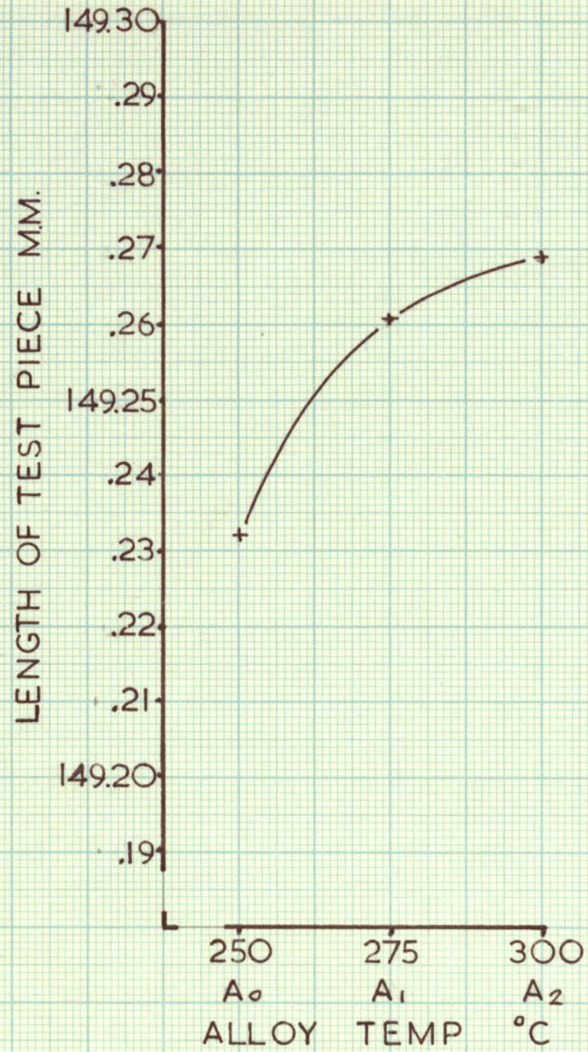


FIGURE 67

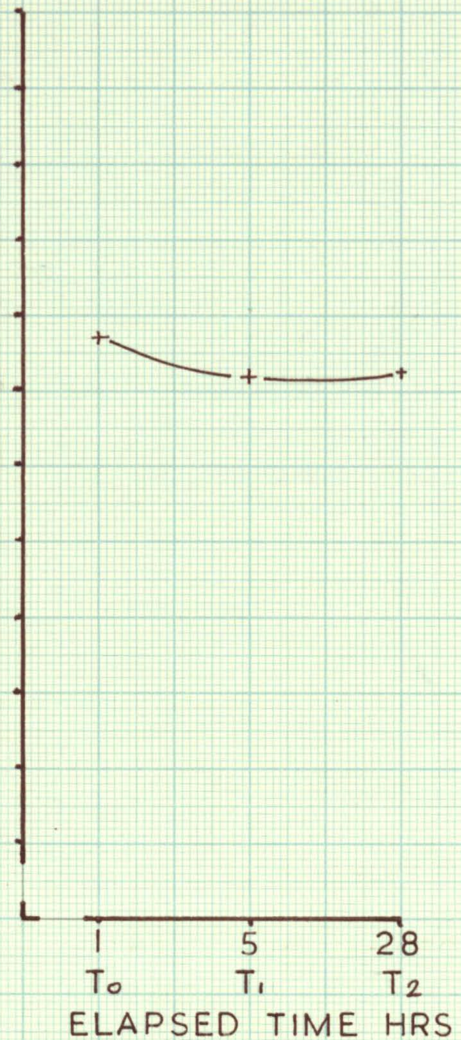


FIGURE 68

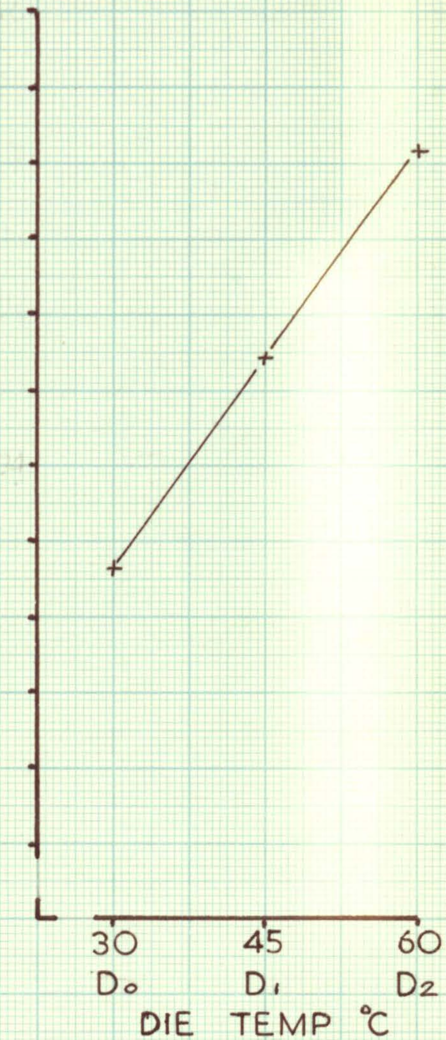


FIGURE 69

3.13.3.

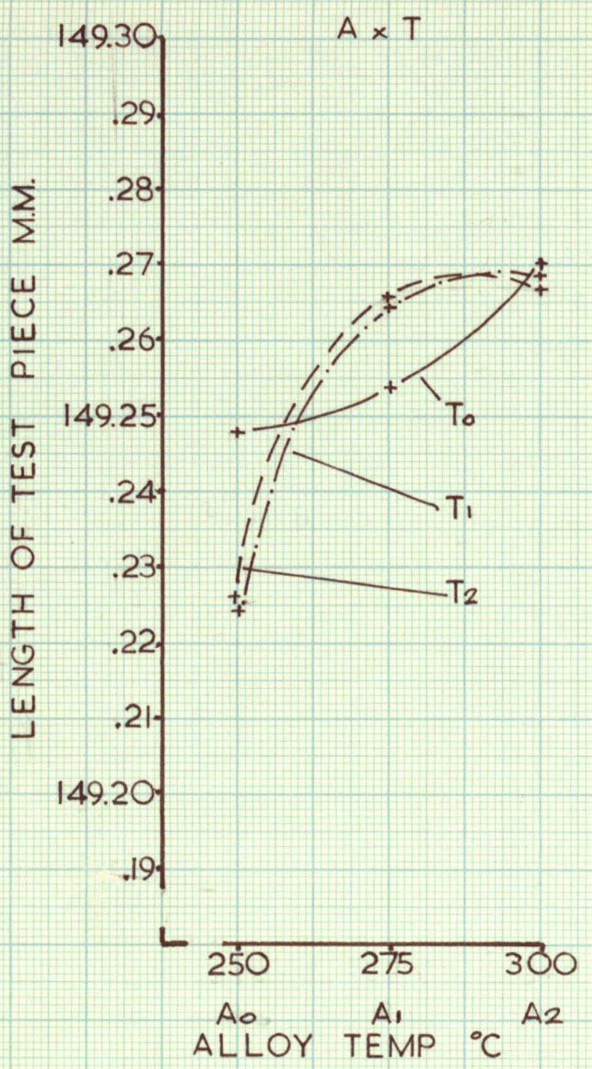


FIGURE 70

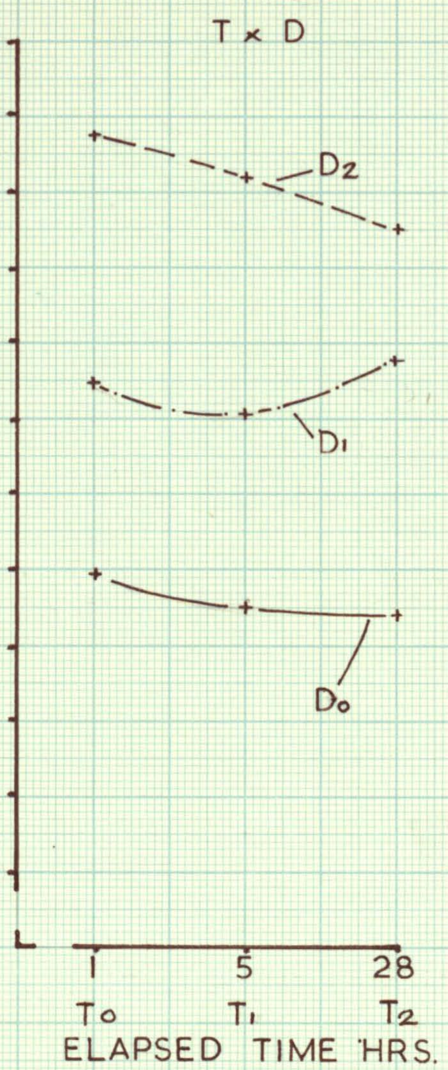


FIGURE 71

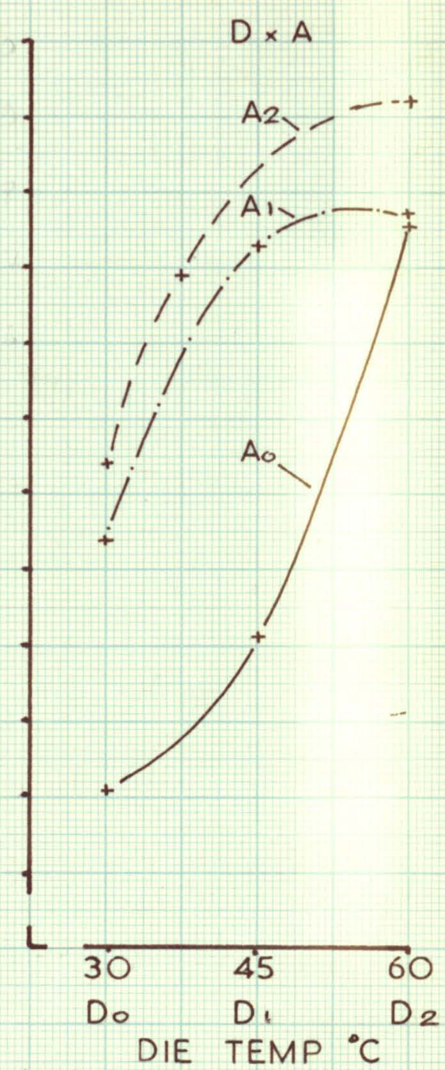


FIGURE 72

3.13.4 Significance of Results

3.13.4.1 Length Change v Alloy Casting Temperature - Figure 67

Statistical significance of results - greater than 99%.

The shrinkage decreased significantly when the pour temperature was increased from 250°C to 300°C. This is partly due to the die expanding when the hotter metal causes the die temperature to rise - see Figure 24.

3.13.4.2 Length Change v Time after Casting - Figure 68

There was no significant change in length between 1 hour and 28 hours after casting, although there was initial shrinkage upon solidification.

3.13.4.3 Length Change v Die Temperature - Figure 69

Statistical significance of results - greater than 99%.

The significant decrease in shrinkage with increase in die temperature is explained by the expansion of the die caused by the higher temperature - Figure 24.

3.13.4.4 Interaction between Alloy Casting Temperature and Time after Casting - Figure 70

Statistical significance of results - greater than 97.5%.

There is a strong interaction. At a pour temperature of 300°C, the shrinkage is the same when measured at 1 hour, 5 hours and 28 hours after cast. At 250°C pour temperature, however, the casting reduced in length between 1 hour and 5 hours after cast, and then stabilised.

3.13.4.5 Interaction between Time after Casting and Die Temperature - Figure 71

There is no statistical interaction.

3.13.4.6 Interaction between Die Temperature and Alloy Casting Temperature - Figure 72

Statistical significance of results - greater than 99%.

There is a very strong interaction. The rate of increase in shrinkage due to rise in die temperature varied depending upon the pour test. The 250°C pour temperature gave the greatest shrinkage.

3.14.

3.14.1. ALLOY:- Frycap 7		DIE TEMPERATURE °C								
TEST:- Holding force kg.		30 D_o			45 D_1			60 D_2		
TIME AFTER CASTING		ALLOY TEMP. °C			ALLOY TEMP. °C			ALLOY TEMP. °C		
		250 A_o	275 A_1	300 A_2	250 A_o	275 A_1	300 A_2	250 A_o	275 A_1	300 A_2
1 HOUR T_o	REPLICATE 1		59.00*				54.00*			198.00
	REPLICATE 2	46.00*		145.00	70.00	40.00		48.00*	54.00	
	RANGE									
	AVERAGE	46.00	59.00	145.00	70.00	40.00	54.00	48.00	54.00	198.00
	SUM									
5 HOURS T_1	REPLICATE 1	16.00*	96.00	21.00*	60.00*	64.00*	107.00	44.00*	55.00*	70.00*
	REPLICATE 2		91.00		16.00*	43.00*	107.00		96.00*	129.00
	RANGE									
	AVERAGE	16.00	93.50	21.00	38.00	53.50	107.00	44.00	75.50	99.50
	SUM									
28 HOURS T_2	REPLICATE 1	43.00		48.00	48.00	91.00		127.00	102.00	
	REPLICATE 2	38.00	11.00*	11.00*			21.00*	59.00		21.00*
	RANGE									
	AVERAGE	40.50	11.00	29.50	48.00	91.00	21.00	93.00	102.00	21.00

* Denotes pin at temperature gauge end of die.

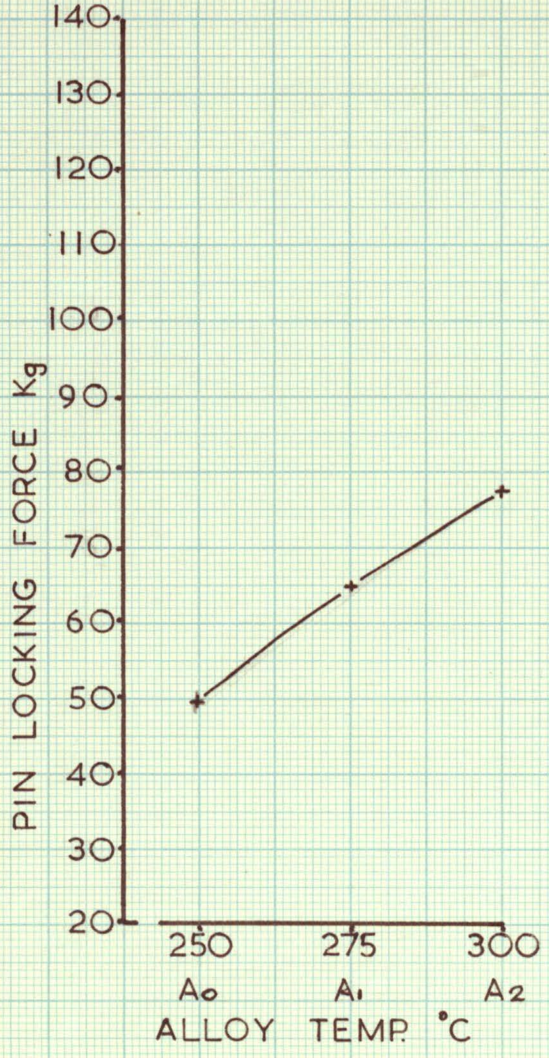


FIGURE 73

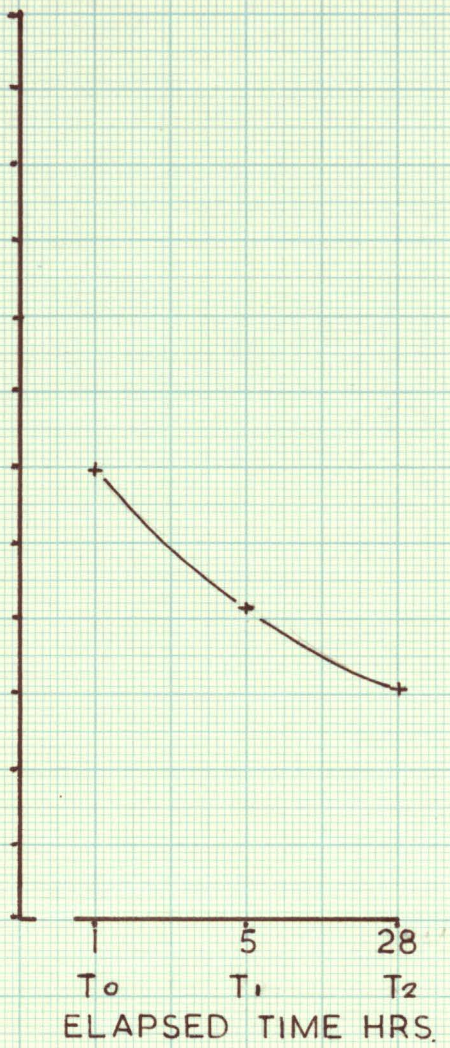


FIGURE 74

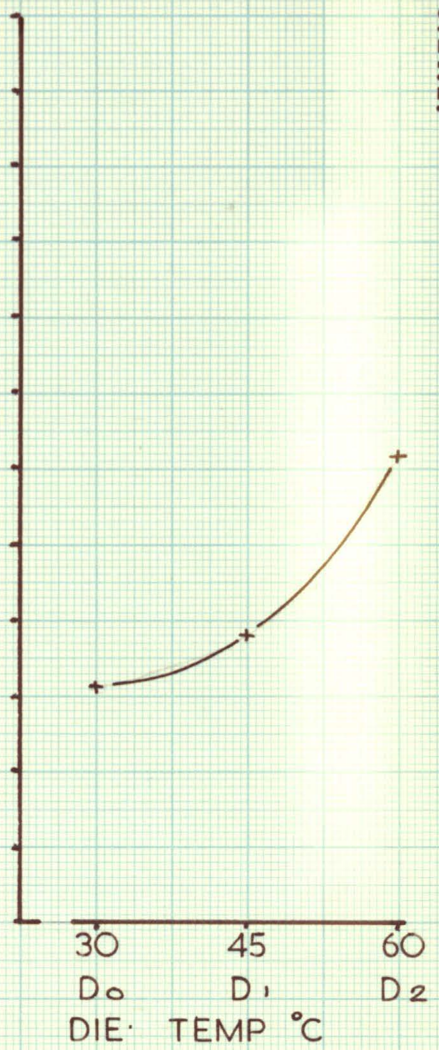


FIGURE 75

FIGURE 76

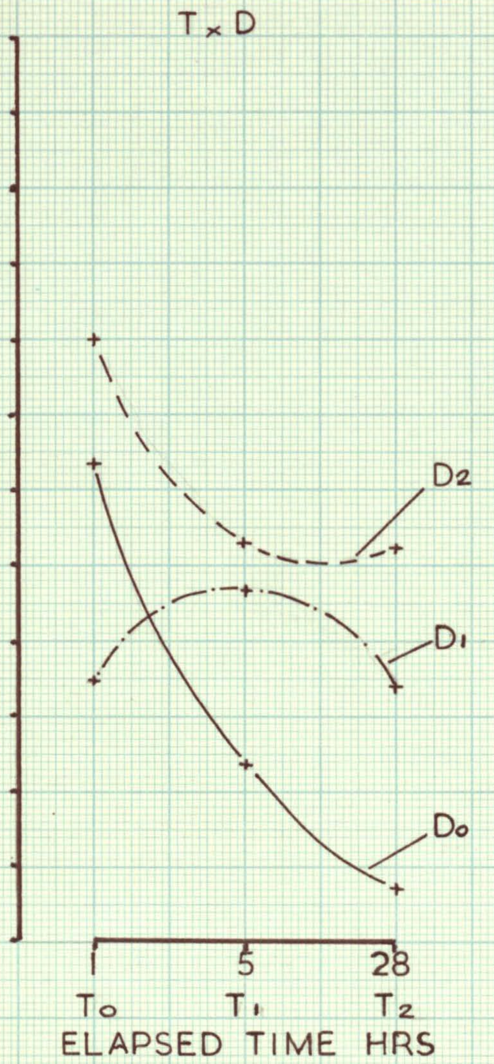


FIGURE 77

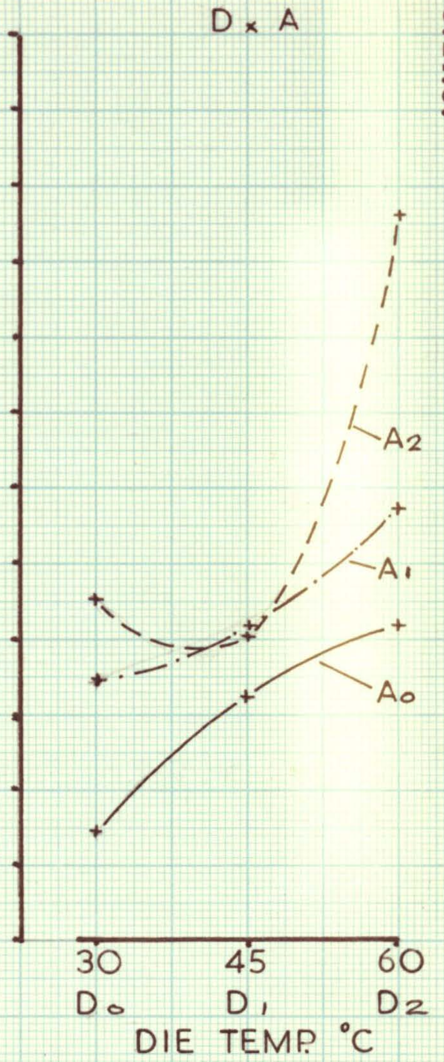


FIGURE 78

3.14.4 Significance of Results

Frycap 7 Holding Force - Figures 73,74,75,76 77 and 78

Statistical significance of results - N.S.

The results obtained, being statistically not significant, represent an experimental failure. The experiment was not replicated and better results may be obtained if this is done. The statistical assumption of normal distribution needs re-examination. Some of the results suggest that a double peaked distribution may be more appropriate. The first peak representing the pins which were held in the block by friction only, and the second peak representing the pins where there was a metallurgical bond. This is of course, only supposition, but more extensive testing could be undertaken to investigate this possibility.

The average holding force for all the Frycap 7 holding force tests was 65Kg.

3.15 Interpretation of Results

3.15.1 Hardness

The average hardness for each of the 3 alloys was:

Cerrotru ...	74	Rockwell	'L'	scale
Cerrocast ...	79	"	"	"
Frycap 7 ...	75	"	"	"

The hardness increased for Cerrotru and Cerrocast with higher pour temperatures. Similarly, hardness increased for Cerrotru and Cerrocast when the die temperature was raised. The die temperature interaction with the pour temperature was very strong. Slower cooling of the alloys resulting from both high die and pour temperatures probably caused the greater hardness.

With the Frycap 7 alloy, whilst higher pour temperatures resulted in greater hardness, higher die temperatures caused a decrease in hardness. The die temperature and pour temperature, whilst strongly inter-related, do have individual characteristics.

3.15.2 Length Change

The Frycap 7 alloy behaved like the majority of metals, by shrinking after solidification. The average length of Frycap 7 test pieces was 149.25 compared to the die size at 60°C of 150.10mm.

Cerrotru and Cerrocast because of their bismuth content grew in length in the 27 hours between the first and last tests. Frycap 7 remained constant.

Increase in pour temperature resulted in greater length for all alloys and only part of this is attributable to the expansion of the die. Further analysis could statistically separate these two effects. Similarly, increase in die temperature gave increase in length but, again, the effects need separating.

The difference between the die size and encapsulation size can be tolerated provided that it is consistent and not excessive. It can be allowed for when designing the encapsulation. Changes after solidification can be troublesome, as it is not usually possible to guarantee that an encapsulated blade will be machined always at the same time after casting.

3.15.3 Holding Force

The experimental results for all three alloys were statistically not significant. The average holding forces for each alloy are valid and these are:

Cerrotru	...	4.5Kg
Cerrocast	...	13Kg
Frycap 7	...	64 Kg

The high figure for Frycap 7 is the result of the high contraction rate of the alloy.

3.15.4 Surface Finish

Observations were kept on the surface finish of the encapsulations.

It was seen that Cerrotru and Cerrocast had appreciably better surface finish than Frycap 7 (Figure 79).

The higher the die temperature and pour temperature, the better the surface finish. This applied to all three alloys.

Photograph showing poor surface finish on Frycap 7 and good surface finish on Cerrotru

(Cerrotru on right)

FIGURE 79

4. CONCLUSIONS

4.1 Choice of Encapsulating Materials

4.1.1 Cerrotru

Cerrotru is very expensive, being about 8 times the price of Frycap 7. Cerrotru is the easiest alloy, of the three considered, to handle, having the lowest melting point. It is softer than Cerrocast. Being an eutectic alloy, solidification takes place over a small temperature range and quicker encapsulation times are possible.

Cerrotru has the poorest holding properties of the three alloys, and where the blade shape is not conducive to being securely held, then the use of Cerrocast or Frycap 7 should be considered.

Cerrotru grows slightly with time, and for very accurate blade work, the time between casting and machining should be consistent.

The surface finish of Cerrotru castings is very good, and is improved when the die and pour temperatures are raised.

Cerrotru is believed to be non-toxic.

4.1.2 Cerrocast

Cerrocast has a fairly wide solidification range 170°C - 138°C which gives longer encapsulation cycle times than Cerrotru.

The surface finished obtained with Cerrocast is very good.

Cerrocast has good blade holding properties and, whilst not as good as Frycap 7, is probably good enough for the majority of blade shapes and blade machining operations.

Cerrocast grows in length with time. This in effect is approximately the same as for Cerrotru and should be taken into consideration for very accurate blade work. Cerrocast is believed to be non-toxic.

4.1.3 Frycap 7

Frycap 7 is inexpensive when compared to Cerrotru and Cerrocast but has a much higher melting point. This necessitates a much higher pouring temperature, giving rise to possible blade distortion during the cooling of the encapsulation. This could be more noticeable with large blades (250 mm long), than with small blades (75 mm long).

The greater contraction of Frycap 7 after casting results in extremely good blade holding and where this is a problem, Frycap 7 should be considered.

The hardness of Frycap 7 is similar to that of Cerrotru, but less than that of Cerrocast. The surface finish is inferior, and this reduces the effective support area of the encapsulation datum faces.

The contraction of Frycap 7 is such that this has to be allowed for in the encapsulation design.

Frycap 7 is a lead based alloy and because of its toxicity, care must be taken in its use to safeguard the health of the operator.

Frycap 7 should be used when high blade holding forces are required.

4.2 Temperature of Alloy at Pour

For Cerrotru, Cerrocast and Frycap 7, the hardness of the encapsulation is greater when the pour temperature is higher.
Higher pour temperatures, unless associated with improved die cooling (this effect has not been tested in this thesis), result in the die expanding to a greater extent giving a larger encapsulation. This effect can be taken into account when designing the encapsulation if it is desired to have high pour temperatures.
Although the holding force tests were inconclusive, there appeared to be a trend with all three alloys to increased holding property with higher pour temperatures.
Surface finish improved with higher pour temperatures.

4.3 Time after Casting

During the period after the encapsulation has cooled after casting, until 27 hours later, the hardness of Cerrotru, Cerrocast and Frycap 7 remains fairly constant. In each case there is a slight peak in hardness at 5 hours but this is not very great. In this period of time, the Cerrotru and Cerrocast encapsulations grow in size but the Frycap decreases in size.
The holding force for all three alloys appears to reduce during this period. The tests performed need repeating for confirmation.

4.4 Die Temperature at Pour

The hardness of Cerrotru and Cerrocast is increased if the die temperature is higher. The reverse is true for Frycap 7.
There is of course a dimensional change in the die when the die temperature is changed. The temperature of the die does not

significantly affect the growth rate which occurs in the 28 hours after cooling.

The blade holding capability of all three alloys appears to be reduced by high temperatures. This is subject to confirmation by further testing.

The effect of die temperature on the encapsulation interacts strongly with the effect of alloy pour temperature, and one should not be altered without considering the associated effect of the other.

5 FURTHER STUDIES

Very little work has been done in the past on the turbine blade encapsulating process and, in particular on the encapsulating materials. The work in this thesis has attempted to:

1) Examine and compare three encapsulating materials
2) assess the effect of varying the die temperature.
3) assess the effect of varying the molten alloy temperature.
4) assess the effect of elapsed time after casting.

Some of the results are contradictory to the previously accepted information available.

As the turbine blade industry is so large and important, it is necessary to improve the encapsulating process - one of the basic techniques used.

Further work is necessary to:

a) find alloys which have good encapsulating properties combined with low cost.
b) design and develop a simple, cheap, low pressure encapsulating machine which could prove economical for the small manufacture of blades.
c) develop a means of swarf separation which would enable the swarf separation and alloy recovery to be performed on the production line.

Each of the above represents a large research programme.

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APPENDIX A

A survey was made into the current encapsulating techniques used by western world turbine blade manufacturers.

Twenty five blade manufacturing companies were sent a questionaire relating to the encapsulation of turbine blades. Twelve companies replied, but two of these declined to give detailed answers.

The answers show the widely varying methods currently being practised. It is hoped that the recommendations given on page 91 will be of benefit to the blade manufacturers and help to improve efficiency.

QUESTIONS

a) Do you encapsulate turbine or compressor blades?

b) What encapsulating material do you use?

c) Do you use a shuttle?

d) What machining process does the encapsulation undergo?

e) Have you tried alternative encapsulating materials and if so so, with what results?

f) What is the die temperature before pouring?

g) What is the molten metal temperature at pouring?

h) Is the metal cast under pressure or gravity?

i) How soon after casting is the encapsulation machined?

j) How do you remove the encapsulating material?

k) To what tolerance do you need to maintain the dimensions between the blade datum and the encapsulation datum face?

l) What are the machining forces involved?

m) What temperature does the blade reach when being machined?

n) Have you the need for improved encapsulating materials, and in what way would they differ from the ones you are currently using?

o) What losses of material do you suffer?

p) How do you reclaim your encapsulating material from your swarf?

COOPER ENERGY SERVICES

Ohio, U.S.A.

a) Turbine blades and stationary turbine vanes.

b) Equivalent alloys to Cerrobend and Cerrocast.

c) We use shuttles and also encapsulate direct.

d) Grinding - milling - drilling - turning.

e) Rigidax was tried some years ago, but with poor results.

f) Ambient.

g) 180^{O}F for 'Cerrobend', 300^{O}F for 'Cerrocast'

h) Gravity.

i) 10 - 12 minutes.

j) Heating in reclaiming tank and fracturing apart.

k) On component datum line 0.002" to 0.004" during encapsulation.
Tolerances from encapsulation face can be as little as 0.0005".

l) Overcome by adequate support to component.

m) 125^{O}F max. This depends on the type of machining taking place.

n) Yes - Lower material costs.

o) 1% per machined component.

p) Reclamation not required, as we have no loss.

DETROIT DIESEL ALLISON

Indiana, U.S.A.

a)Turbine blades only. We buy our compressor blades.

b) Blades - Cerrobend, Vanes - Cerrocast.

c) Yes, but we also encapsulate direct.

d) Blades - grinding and EDM. Vanes - turning and grinding.

e) Others were tried 15 years ago, but those in b) have used for 15 years.

f) Shuttle and vanes at ambient Blades at - 18^{O}C.

g) Cerrobend 160^{O}F, Cerrocast 300^{O}F.

h) Gravity.

i) 24 hours.

j) Cerrobend - hot water, Cerrocast - hot oil.

k) $\pm$0.0005".

l) Grinding.

m) 500^{O}F estimated, but blade is constantly cooled by flooding with coolant.

n) We do not anticipate a change.

o) 5 - 10%.

p) We do not reclaim.

GENERAL ELECTRIC CO.

Boston, U.S.A.

a) Both.

b) Cerrobend

c) Yes.

d) Endmilling tenon (PEG) on tip end of blade, using (2) spindle tracer milling machine.

e) No.

f) Ambient.

g) 158^{o}F.

h) Gravity.

i) 15 - 30 minutes.

j) Electric melting pot.

k) $\pm$ 0.0003".

l) Minimal - 2½HP max. per spindle.

m) Flood coolant keeps temperature from rising significantly.

n) No.

o) Minimal.

p) No swarf loss.

KELSEY - HAYES CO.

Utica, U.S.A.

a) Both.

b) Cerrobend.

c) Yes

d) Grinding of dovetail.

e) Yes, plastic but with negative results.

f) Room temperature.

g) 170°F.

h) Gravity.

i) 1 hour or more.

j) Submersion in boiling water.

k) $\pm$ 0.001",

l) No forces given.

m) 200°F.

n) Yes.

o) Yes.

p) We do not reclaim material.

GENERAL ELECTRIC CO.

Vermont, U.S.A.

a) Both

b) Type metal

c) No - we encapsulate direct.

d) Milling - broaching - turning - drilling -grinding

e) Yes, but poor results.

f) Water - cooled.

g) 600°F.

h) Both.

i) Sometimes ½ hour, sometimes weeks.

j) Submersion in molten type metal.

k) ± 0.001".

l) see d) - forces not given.

m) 120°F max.

n) Yes. Lower cost and better holding capability.

o) This information is confidential.

p) We do not reclaim.

MASCHINENFABRIK PAUL LEISTRITZ

Nürnberg, West Germany

a) Compressor blades and vanes

b) Cerrotru.

c) No - we encapsulate direct.

d) The encapsulation is done in the Cirrus machine
- rotating table. Then, milling - grinding.

e) Cerrobend - with good results.

f) 60°C.

g) 170°C

h) Gravity.

i) Within 10 weeks.

j) The melting out is done in the Cirrus machine.

k) ± 0.02 mm,

l) No answer given.

m) Room temperature.

n) Yes - lower price. Cerrobend and Cerrotru are technically satisfactory.

o) 5 - 10%.

p) Swarf returned to supplier for reclamation.

CENTRAX LTD.

Newton Abbot, England

a) Both.

b) Cerrotru and another, similar to Cerrobend.

c) Yes, and we also encapsulate direct.

d) Turning - milling - grinding - drilling.

e) Rigidax - with poor results. Components moved under load and residues were difficult to remove.

f) 30°C for Cerrotru.

g) 150°C for Cerrotru, 100°C for other alloy.

h) Gravity.

i) Between a few minutes and several days.

j) Cerrotru - hot oil. Other alloy - hot water.

k) 0.004" - 0.005".

l) Fairly high on turning, low on other operations.

m) Ambient.

n) Existing materials satisfactory except for high price.

o) 1 - 3%.

p) Cerrotru, pot furnace and ladle. Other alloy, no loss.

A.E. TURBINE COMPONENTS LTD

Leeds, England

a) Both.

b) Rigidax or Cerrotru.

c) Yes - and we also encapsulate direct.

d) Grinding - broaching - milling.

e) No.

f) No accurate control.

g) No accurate control.

h) Gravity.

i) One hour +

j) Melt out.

k) $\pm$ 0.025 mm.

l) Don't know.

m) Don't know.

n) Yes - improved stability.

o) 5 - 10%.

p) Subcontract (centrifuge).

UNIVERSAL TURBINE BLADES LTD

Sheffield, England

a) Both.

b) Cerrotru.

c) No - we encapsulate direct.

d) Milling - broaching

e) No.

f) 40°C.

g) 160°C

h) Gravity.

i) Immediately.

j) Submersion in hot oil.

k) 0.001".

l) Variable. Additional support often necessary.

m) Insignificant.

n) Yes - improved adhesion and increased hardness, to improve tolerance on datum and reduce movement of component within block during machining.

o) 5%.

p) Centrifuge/Re-melt.

ROLLS ROYCE LTD.

Glasgow, Scotland

a) Compressor vanes and rotors.

b) Cerrotru and Frycap 7

c) No - we encapsulate direct.

d) Broaching.

e) Alternative lead based alloys were tried when developing use of Frycap 7.

f) 10 - 20^{o}C.

g) 160^{o}C for Cerrotru, 320^{o}C for Frycap 7.

h) Gravity for Cerrotru, Frycap 7 injected at 350psi.

i) Between 1 and 12 hours.

j) Cerrotru in hot oil, Frycap 7 in molten lead.

k) Between 0.0005" and 0.002", depending on the size of the encapsulation.

l) Between 2,000 and 5,000 lbs cut load.

m) No figure available, but heat generated not great.

n) Yes - lower cost, but retaining properties of Cerrotru.

o) This information is confidential.

p) Swarf is returned to suppliers for reclamation.

APPENDIX B

STATISTICAL CALCULATIONS

Cerrotru - Hardness

Sum of 27 observation totals = 3997.30

Crude sum of squares = 296424.863

Correction = 295896.4313

Total sum of squares about mean = 528.4317

A X T	A o	A 1	A 2	SUM
To	421.740	438.620	465.440	1325.800
T1	429.680	445.180	463.920	1338.780
T2	428.340	446.000	458.380	1332.720
SUM	1279.760	1329.800	1387.740	3997.300

T X D	T o	T 1	T 2	SUM
Do	429.940	432.580	435.340	1297.860
D1	438.240	444.900	443.420	1326.560
D2	457.620	461.300	453.960	1372.880
SUM	1325.800	1338.780	1332.720	3997.300

D X A	D o	D 1	D 2	SUM
Ao	415.600	422.480	441.680	1279.760
A1	428.080	440.280	461.440	1329.800
A2	454.180	463.800	469.760	1387.740
SUM	1297.860	1326.560	1372.880	3997.300

A X T	A o	A 1	A 2	AVERAGE
To	70.2900	73.1033	77.5733	73.6555
T1	71.6133	74.1967	77.3200	74.3766
T2	71.3900	74.3333	76.3967	74.0400
AVERAGE	71.0977	73.8777	77.0966	74.0241

T X D	T o	T 1	T 2	AVERAGE
Do	71.6567	72.0967	72.5567	72.1033
D1	73.0400	74.1500	73.9033	73.6977
D2	76.2700	76.8833	75.6600	76.2711
AVERAGE	73.6555	74.3766	74.0400	74.0241

D X A	D o	D 1	D 2	AVERAGE
Ao	69.2667	70.4133	73.6133	71.0977
A1	71.3467	73.3800	76.9067	73.8777
A2	75.6967	77.3000	78.2933	77.0966
AVERAGE	72.1033	73.6977	76.2711	74.0241

A x T table S.S. = 296236.9678 - 295896.4313

= 340.5365

T x D table S.S. = 296066.636 - 295896.4313

= 170.2047

D x A table S.S. = 296397.3568 - 295896.4313

= 500.9255

Main effects

S.S. for A	=	296220.8892 - 295896.4313
	=	324.4579
S.S. for T	=	295901.1182 - 295896.4313
	=	4.6869
S.S. for D	=	296055.6393 - 295896.4313
	=	159.208

Interaction S.S. for A x T	=	340.5365 - (4.6869 + 324.4579)
	=	11.3917
Interaction S.S. for T x D	=	170.2047 - (4.6869 + 159.208)
	=	6.3098
Interaction S.S. for D x A	=	500.9255 - (324.4579 + 159.208)
	=	17.2596

Three factor interaction A x T x D	=	528.4317 - (4.6869 + 324.4579
		+ 159.208 + 11.3917 + 6.3098
		+ 17.2596)
	=	5.1178

Sum of 54 observations	=	3997.3
Crude S.S. of 54 observations	=	296439.986
Correction	=	295896.4313
Total S.S. about mean	=	543.5547

SOURCE OF VARIATION	SUM OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARE	VARIANCE RATIO	SIGNIFI - CANCE
MAIN EFFECTS					
A	324.4579	2	162.22895	289.6428	* * *
T	4.6869	2	2.34345	4.184	*
D	159.208	2	79.604	142.1246	* * *
TWO FACTOR INTERACTION					
A x T	11.3917	4	2.847925	5.0847	* * *
T x D	6.3098	4	1.57745	2.8164	*
D xA	17.2596	4	4.3149	7.7038	* * *
THREE FACTOR INTERACTION					
A x T x D	5.1178	8	0.6397	1.142	N.S
REMAINDER = ERROR	15.123000	27	0.5601		
TOTAL:-	543.554700	53			

N.S. – NOT SIGNIFICANT
* – > 95%
** – > 97.5%
*** – > 99%

Cerrotru - Length Change

Sum of 27 observation totals	=	7.275
Crude sum of squares	=	1.0385525
Correction	=	0.9801042
Total sum of squares about mean	=	0.0584483

A X T	A o	A 1	A 2	SUM
To	0.583	0.786	0.707	2.076
T1	0.745	0.852	0.786	2.383
T2	0.833	1.024	0.959	2.816
SUM	2.161	2.662	2.452	7.275

T X D	T o	T 1	T 2	SUM
Do	0.699	0.761	0.882	2.342
D1	0.646	0.769	0.942	2.357
D2	0.731	0.853	0.992	2.576
SUM	2.076	2.383	2.816	7.275

D X A	D o	D 1	D 2	SUM
Ao	0.707	0.836	0.618	2.161
A1	0.691	0.763	1.208	2.662
A2	0.944	C.758	0.750	2.452
SUM	2.342	2.357	2.576	7.275

A X T	A o	A 1	A 2	AVERAGE
To	0.097	0.131	0.118	0.115
T1	0.124	0.142	0.131	0.132
T2	0.139	0.171	0.160	0.156
AVERAGE	0.120	0.148	0.136	0.135

T X D	T o	T 1	T 2	AVERAGE
Do	0.117	0.127	0.147	0.130
D1	0.108	0.128	0.157	0.131
D2	0.122	0.142	0.165	0.143
AVERAGE	0.115	0.132	0.156	0.135

D X A	D o	D 1	D 2	AVERAGE
Ao	0.118	0.139	0.103	0.120
A1	0.115	0.127	0.201	0.148
A2	0.157	0.126	0.125	0.136
AVERAGE	0.130	0.131	0.143	0.135

A x T table S.S. = 1.0030675 - 0.9801042

= 0.0229633

T x D table S.S. = 0.9979535 - 0.9801042

= 0.0178493

D x A table S.S. = 1.02129717 - 0.9801042

= 0.04119297

Main effects

S.S. for A	=	0.987137 - 0.9801042
	=	0.007032966
S.S. for T	=	0.995462 - 0.9801042
	=	0.01535808
S.S. for D	=	0.9820105 - 0.9801042
	=	0.0019063

Interaction S.S. for A x T	=	0.0229633 - (0.015358 + 0.00703296)
	=	0.00057234
Interaction S.S. for T x D	=	0.0178493 - (0.015358 + 0.0019063)
	=	0.000585
Interaction S.S. for D x A	=	0.04119297 - (0.00703296 + 0.0019063)
	=	0.0322537

Three factor interaction A x T x D	=	0.0584483 - (0.01535808 + 0.007033 + 0.0019063 + 0.00057234 + 0.000585 + 0.032254)
	=	0.00074

Sum of 54 observations	=	7.275
Crude S.S. of 54 observations	=	1.041337
Correction	=	0.9801042
Total S.S. about mean	=	0.0612328

SOURCE OF VARIATION	SUM OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARE	VARIANCE RATIO	SIGNIFI - CANCE
MAIN EFFECTS					
A	0.007033	2	0.0035	35.000	* * *
T	0.015358	2	0.0076	7.600	* * *
D	0.001906	2	0.00095	9.500	* * *
TWO FACTOR INTERACTION					
A x T	0.000572	4	0.00014	1.400	N.S
T x D	0.000585	4	0.00014	1.400	N.S
D x A	0.032254	4	0.00800	80.000	* * *
THREE FACTOR INTERACTION					
A x T x D	0.00074	8	0.00009	0.900	N.S
REMAINDER = ERROR	0.002784	27	0.0001		
TOTAL:-	0.061233	53			

N.S – NOT SIGNIFICANT

* – 95%

** – 97.5%

*** – 99%

Cerrotru - Holding Force

Sum of 27 observations	=	127.825
Crude sum of squares	=	1543.561
Correction	=	605.1567
Total sum of squares about mean	=	938.4043

A X T	A o	A1	A2	SUM
To	18.875	42.100	12.500	73.475
T1	2.500	1.500	18.250	22.250
T2	6.600	10.500	15.000	32.100
SUM	27.975	54.100	45.750	127.825

T X D	T o	T 1	T 2	SUM
Do	6.350	9.500	9.750	25.600
D1	30.625	1.000	10.750	42.375
D2	36.500	11.750	11.600	59.850
SUM	73.475	22.250	32.100	127.825

D X A	D o	D 1	D 2	SUM
Ao	7.250	6.125	14.600	27.975
A1	5.350	20.750	28.000	54.100
A2	13.000	15.500	17.250	45.750
SUM	25.600	42.375	59.850	127.825

A X T	A o	A 1	A 2	AVERAGE
To	6.292	14.033	4.167	8.164
T1	0.833	0.500	6.083	2.472
T2	2.200	3.500	5.000	3.567
AVERAGE	3.108	6.011	5.083	4.734

T X D	T o	T 1	T 2	AVERAGE
Do	2.117	3.167	3.250	2.844
D1	10.208	0.333	3.583	4.708
D2	12.167	3.917	3.867	6.650
AVERAGE	8.164	2.472	3.567	4.734

D X A	D o	D 1	D 2	AVERAGE
Ao	2.417	2.042	4.867	3.108
A1	1.783	6.917	9.333	6.011
A2	4.333	5.167	5.750	5.083
AVERAGE	2.844	4.708	6.650	4.734

A x T table S.S. = 1001.766 - 605.1567

= 396.6093

T x D table S.S. = 961.654 - 605.1567

= 356.4973

D x A table S.S. = 751.0785 - 605.1567

= 145.9218

Main effects

S.S. for A	=	644.71922 - 605.1567
	=	39.56252
S.S. for T	=	769.33866 - 605.1567
	=	164.18196
S.S. for D	=	670.33589 - 605.1567
	=	65.17919

Interaction S.S. for A x T	=	396.6093 - (164.18196 + 39.56252)
	=	192.86482
Interaction S.S. for T x D	=	356.4973 - (164.18196 + 65.17919)
	=	127.13615
Interaction S.S. for D x A	=	145.9218 - (39.56252 + 65.17919)
	=	41.18009

Three factor interaction A x T x D	=	938.4043 - (164.18196
		+ 39.56252 + 65.17919
		+ 192.86482 + 127.13615
		+ 41.18009)
	=	308.29957

SOURCE OF VARIATION	SUM OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARE	VARIANCE RATIO	SIGNIFI - CANCE
MAIN EFFECTS					
A	39.56252	2	19.781	0.51	N.S
T	164.18196	2	82.091	2.13	N.S
D	65.17919	2	32.590	0.85	N.S
TWO FACTOR INTERACTION					
A x T	192.86482	4	48.216	1.25	N.S
T x D	127.13615	4	31.784	0.82	N.S
D x A	41.18009	4	10.295	0.27	N.S
THREE FACTOR INTERACTION					
A x T x D	308.29957	8	38.537		
TOTAL:-	938.4043	26			

N.S - NOT SIGNIFICANT
* - > 95%
** - > 97.5%
*** - > 99%

Cerrocast - Hardness

Sum of 27 observation totals	=	4246.10
Crude sum of squares	=	334033.1946
Correction	=	333877.1335
Total sum of squares about mean	=	156.0611

A X T	A o	A 1	A 2	SUM
To	469.420	464.960	476.740	1411.120
T1	467.840	469.140	485.220	1422.200
T2	465.160	466.040	481.580	1412.780
SUM	1402.420	1400.140	1443.540	4246.100

T X D	T o	T 1	T 2	SUM
Do	463.320	468.560	469.820	1401.700
D1	470.440	476.960	473.000	1420.400
D2	477.360	476.680	469.960	1424. 00
SUM	1411.120	1422.200	1412.780	4246.100

D X A	D o	D 1	D 2	SUM
Ao	459.160	474.040	469.220	1402.420
A1	468.020	457.340	474.780	1400.140
A2	474.520	489.020	480.000	1443.540
SUM	1401.700	1420.400	1424.000	4246.100

A X T	A o	A 1	A 2	AVERAGE
To	78.2366	77.4933	79.4566	78.3955
T1	77.9733	78.1900	80.8700	79.0111
T2	77.5266	77.6733	80.2633	78.4877
AVERAGE	77.9122	77.7855	80.1966	78.6315

T X D	T o	T 1	T 2	AVERAGE
Do	77.2200	78.0933	78.3033	77.8722
D1	78.4066	79.4933	78.8333	78.9111
D2	79.5600	79.4466	78.3266	79.1111
AVERAGE	78.3955	79.0111	78.4877	78.6315

D X A	D o	D 1	D 2	AVERAGE
Ao	76.5266	79.0066	78.2033	77.9122
A1	78.0033	76.2233	79.1300	77.7855
A2	79.0866	81.5033	80.0000	80.1966
AVERAGE	77.8722	78.9111	79.1111	78.6315

A x T table S.S. = 333952.5705 - 333877.1335

= 75.437

T x D table S.S. = 333906.1929 - 333877.1335

= 29.059366

D x A table S.S. = 334006.2785 - 333877.1335

= 129.145

Main effects

S.S. for A	=	333943.42266 - 333877.1335
	=	66.289166
S.S. for T	=	333881.1013 - 333877.1335
	=	3.967766
S.S. for D	=	333893.05833 - 333877.1335
	=	15.924833

Interaction S.S. for A x T	=	75.437 - (3.967766 + 66.289166)
	=	5.180068
Interaction S.S. for T x D	=	29.059366 - (3.967766 + 15.924833)
	=	9.166767
Interaction S.S. for D x A	=	129.145 - (66.289166 + 15.924833)
	=	46.931001

Three factor interaction A x T x D = 156.0611 - (66.289166
+ 3.967766 + 15.924833
+ 5.180068 + 9.166767
+ 46.931001)
= 8.601499

Sum of 54 observations	=	4246.10
Crude S.S. of 54 observations	=	334090.25
Correction	=	333877.1335
Total S.S. about mean	=	213.1165

SOURCE OF VARIATION	SUM OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARE	VARIANCE RATIO	SIGNIFI - CANCE
MAIN EFFECTS					
A	66.289166	2	33.1446	15.686	* * *
T	3.967766	2	1.9838	0.9388	N.S
D	15.924833	2	7.9624	3.768	*
TWO FACTOR INTERACTION					
A x T	5.180068	4	1.295	0.6129	N.S
T x D	9.166767	4	2.2917	1.0846	N.S
D x A	46.931001	4	11.7328	5.5527	* * *
THREE FACTOR INTERACTION					
A x T x D	8.601499	8	1.075	0.51	N.S
REMAINDER = ERROR	57.055400	27	2.113		
TOTAL:-	213.116500	53			

N.S - NOT SIGNIFICANT
* - > 95%
** - > 97.5%
*** - > 99%

Cerrocast - Length Change

Sum of 27 observation totals = 10.97

Crude sum of squares = 2.268987

Correction = 2.228535

Total sum of squares about mean = 0.0404518

A X T	A o	A 1	A 2	SUM
To	0.956	1.124	1.165	3.245
T1	1.102	1.261	1.228	3.591
T2	1.326	1.412	1.396	4.134
SUM	3.384	3.797	3.789	10.970

T X D	T o	T 1	T 2	SUM
Do	1.126	1.250	1.414	3.790
D1	1.001	1.146	1.302	3.449
D2	1.118	1.195	1.418	3.731
SUM	3.245	3.591	4.134	10.970

D X A	D o	D 1	D 2	SUM
Ao	1.240	1.002	1.142	3.384
A1	1.234	1.174	1.389	3.797
A2	1.316	1.273	1.200	3.789
SUM	3.790	3.449	3.731	10.970

A X T	A o	A 1	A 2	AVERAGE
To	0.1593	0.1873	0.1942	0.1803
T1	0.1836	0.2102	0.2046	0.1995
T2	0.2210	0.2353	0.2326	0.2297
AVERAGE	0.1880	0.2109	0.2105	0.2031

T X D	T o	T 1	T 2	AVERAGE
Do	0.1876	0.2750	0.2356	0.2106
D1	0.1668	0.1910	0.2170	0.1916
D2	0.1863	0.1992	0.2363	0.2073
AVERAGE	0.1803	0.1995	0.2297	0.2031

D X A	D o	D 1	D 2	AVERAGE
Ao	0.2066	0.1670	0.1903	0.1880
A1	0.2056	0.1956	0.2315	0.2109
A2	0.2193	0.2122	0.2000	0.2105
AVERAGE	0.2106	0.1916	0.2073	0.2031

A x T table S.S. = 2.257980 - 2.228535

= 0.029445

T x D table S.S. = 2.254828 - 2.228535

= 0.026293

D x A table S.S. = 2.244751 - 2.228535

= 0.016216

Main effects

S.S. for A	=	2.234732 - 2.228535
	=	0.0061976
S.S. for T	=	2.250848 - 2.228535
	=	0.022313
S.S. for D	=	2.232225 - 2.228535
	=	0.0036907

Interaction S.S. for A x T	=	0.029445 - (0.022313 + 0.0061976)
	=	0.0009344
Interaction S.S. for T x D	=	0.026293 - (0.022313 + 0.0036907)
	=	0.0002893
Interaction S.S. for D x A	=	0.016216 - (0.0061976 + 0.0036907)
	=	0.0063277

Three factor interaction A x T x D	=	0.0404518 - (0.022313 + 0.0061976 + 0.0036907 + 0.0009344 + 0.0002893 + 0.0063277)
	=	0.0006991

Sum of 54 observations	=	10.97
Crude S.S. of 54 observations	=	2.271388
Correction	=	2.228535
Total S.S. about mean	=	0.0428528

SOURCE OF VARIATION	SUM OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARE	VARIANCE RATIO	SIGNIFI - CANCE
MAIN EFFECTS					
A	0.006198	2	0.0031	34.750	* * *
T	0.022313	2	0.0111	124.800	* * *
D	0.003691	2	0.0018	20.690	* * *
TWO FACTOR INTERACTION					
A x T	0.000934	4	0.000233	2.620	N.S
T x D	0.000289	4	0.000072	0.810	N.S
D x A	0.006328	4	0.00158	17.760	* * *
THREE FACTOR INTERACTION					
A x T x D	0.0006991	8	0.000087	0.978	N.S
REMAINDER = ERROR	0.002401	27	0.000089		
TOTAL:-	0.042853	53			

N.S - NOT SIGNIFICANT
* - > 95%
** - > 97.5%
*** - > 99%

Cerrocast - Holding Force

Sum of 27 observations	=	359.100
Crude sum of squares	=	5767.585
Correction	=	4776.030
Total sum of squares about mean	=	991.555

A X T	A o	A 1	A 2	SUM
To	48.250	54.000	44.250	146.500
T1	38.600	39.250	50.750	128.600
T2	23.250	24.250	36.500	84.000
SUM	110.100	117.500	131.500	359.100

T X D	T o	T 1	T 2	SUM
Do	46.000	33.500	20.000	99.500
D1	53.750	62.100	32.750	148.600
D2	46.750	33.000	31.250	111.000
SUM	146.500	128.600	84.000	359.100

D X A	D o	D 1	D 2	SUM
Ao	27.500	47.600	35.000	110.100
A1	44.000	37.250	36.250	117.500
A2	28.000	63.750	39.750	131.500
SUM	99.500	148.600	111.000	359.100

A X T	A o	A 1	A 2	AVERAGE
To	16.083	18.000	14.750	16.278
T1	12.867	13.083	16.917	14.289
T2	7.750	8.083	12.167	9.333
AVERAGE	12.223	13.056	14.611	13.300

T X D	T o	T 1	T 2	AVERAGE
Do	15.333	11.167	6.667	11.056
D1	17.917	20.700	10.917	16.511
D2	15.583	11.000	10.417	12.333
AVERAGE	16.278	14.289	9.333	13.300

D X A	D o	D 1	D 2	AVERAGE
Ao	9.167	15.867	11.667	12.223
A1	14.667	12.417	12.083	13.056
A2	9.333	21.250	13.250	14.611
AVERAGE	11.056	16.511	12.333	13.300

A x T table S.S. = 5089.695 - 4776.03

= 313.665

T x D table S.S. = 5235.803 - 4776.03

= 459.773

D x A table S.S. = 5104.253 - 4776.03

= 328.223

Main effects

S.S. for A	= 4802.2788 - 4776.03
	= 26.2488
S.S. for T	= 5006.2455 - 4776.03
	= 230.2155
S.S. for D	= 4922.5788 - 4776.03
	= 146.5488

Interaction S.S. for A x T	= 313.665 - (230.2155 + 26.2488)
	= 57.2007
Interaction S.S. for T x D	= 459.773 - (230.2155 + 146.5488)
	= 83.0087
Interaction S.S. for D x A	= 328.223 - (26.2488 + 146.5488)
	= 155.4254

Three factor interaction A x T x D	= 991.555 - (230.2155 +
	26.2488 + 146.5488 + 57.2007
	+ 83.0087 + 155.4254)
	= 292.9071

SOURCE OF VARIATION	SUM OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARE	VARIANCE RATIO	SIGNIFI - CANCE
MAIN EFFECTS					
A	26.2488	2	13.1244	0.360	N.S
T	230.2155	2	115.1078	3.144	N.S
D	146.5488	2	73.2744	2.001	N.S
TWO FACTOR INTERACTION					
A x T	57.2007	4	14.3002	0.391	N.S
T x D	83.0087	4	20.7522	0.567	N.S
D x A	155.4254	4	38.8564	1.061	N.S
THREE FACTOR INTERACTION					
A x T x D	292.9071	8	36.6134		
TOTAL:-	991.555	26			

N.S - NOT SIGNIFICANT
* - > 95%
** - > 97.5%
*** - > 99%

Frycap 7 - Hardness

Sum of 27 observation totals	=	4063.18
Crude sum of squares	=	305862.7778
Correction	=	305730.2169
Total sum of squares about mean	=	132.5609

A X T	A o	A 1	A 2	SUM
To	441.360	453.060	458.460	1352.880
T1	444.720	452.900	463.600	1361.220
T2	443.840	448.300	456.940	1349.080
SUM	1329.920	1354.260	1379.000	4063.180

T X D	T o	T 1	T 2	SUM
Do	457.920	459.160	451.120	1368.200
D1	450.900	453.560	452.140	1356.600
D2	444.060	448.500	445.820	1338.380
SUM	1352.880	1361.220	1349.080	4063.180

D X A	D o	D 1	D 2	SUM
Ao	449.440	441.540	438.940	1329.920
A1	460.360	447.400	446.500	1354.260
A2	458.400	467.660	452.940	1379.000
SUM	1368.200	1356.600	1338.380	4063.180

A X T	A o	A 1	A 2	AVERAGE
To	73.5600	75.5100	76.4100	75.1600
T1	74.1200	75.4833	77.2667	75.6233
T2	73.9733	74.7167	76.1567	74.9488
AVERAGE	73.8844	75.2366	76.6111	75.2441

T X D	T o	T 1	T 2	AVERAGE
Do	76.3200	76.5267	75.1867	76.0110
D1	75.1500	75.5933	75.3567	75.3667
D2	74.0100	74.7500	74.3030	74.3544
AVERAGE	74.1600	75.6233	74.9488	75.2441

D X A	D o	D 1	D 2	AVERAGE
Ao	74.9060	73.5900	73.1560	73.8840
A1	76.7260	74.5600	74.4160	75.2360
A2	76.4000	77.9430	75.4900	76.6111
AVERAGE	76.0110	75.3667	74.3544	75.2441

A x T table S.S. = 305804.6387 - 305730.2169

= 74.4218

T x D table S.S. = 305763.8259 - 305730.2169

= 33.609033

D x A table S.S. = 305845.6046 - 305730.2169

= 115.3877

Main effects

S.S. for A	=	305797.1308 - 305730.2169
	=	66.913877
S.S. for T	=	305734.5016 - 305730.2169
	=	4.284722
S.S. for D	=	305755.32355 - 305730.2169
	=	25.10665

Interaction S.S. for A x T	=	74.4218 - (4.284722 + 66.913877)
	=	3.223201
Interaction S.S. for T x D	=	33.609033 - (4.284722 + 25.10665)
	=	4.217661
Interaction S.S. for D x A	=	115.3877 - (66.913877 + 25.10665)
	=	23.367173

Three factor interaction A x T x D = 132.5609 - (4.284722
+ 66.913877 + 25.10665
+ 3.223201 + 4.217661
+ 23.367173)
= 5.447616

Sum of 54 observations	=	4063.18
Crude S.S. of 54 observations	=	305886.8964
Correction	=	305730.2169
Total S.S. about mean	=	156.6795

SOURCE OF VARIATION	SUM OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARE	VARIANCE RATIO	SIGNIFI - CANCE
MAIN EFFECTS					
A	66.913877	2	33.457	37.454	* * *
T	4.284722	2	2.142	2.398	N.S
D	25.10665	2	12.553	14.053	* * *
TWO FACTOR INTERACTION					
A x T	3.223201	4	0.806	0.902	N.S
T x D	4.217661	4	1.054	1.180	N.S
D x A	23.367173	4	5.842	6.540	* * *
THREE FACTOR INTERACTION					
A x T x D	5.447616	8	0.681	0.762	N.S
REMAINDER = ERROR	24.118600	27	0.89328		
TOTAL:-	156.6795	53			

N.S - NOT SIGNIFICANT
* - > 95%
** - > 97.5%
*** - > 99%

Frycap 7 - Length Change

Sum of 27 observation totals = 13.708

Crude sum of squares = 3.52906

Correction = 3.47980

Total sum of squares about mean = 0.04926

A X T	A O	A 1	A 2	SUM
T o	1.486	1.522	1.620	4.628
T1	1.344	1.586	1.610	4.540
T2	1.352	1.588	1.600	4.540
SUM	4.182	4.696	4.830	13.708

T X D	T O	T 1	T 2	SUM
Do	1.376	1.350	1.344	4.070
D1	1.528	1.502	1.546	4.576
D2	1.724	1.688	1.650	5.062
SUM	4.628	4.540	4.540	13.708

D X A	D O	D 1	D 2	SUM
Ao	1.204	1.326	1.652	4.182
A1	1.402	1.636	1.658	4.696
A2	1.464	1.614	1.752	4.830
SUM	4.070	4.576	5.062	13.708

A X T	A o	A 1	A 2	AVERAGE
To	0.2477	0.2537	0.2700	0.25711
T1	0.2240	0.2643	0.2683	0.25222
T2	0.2253	0.2647	0.2667	0.25222
AVERAGE	0.23233	0.26089	0.26833	0.25385

T X D	T o	T 1	T 2	AVERAGE
Do	0.2293	0.2250	0.2240	0.22611
D1	0.2547	0.2503	0.2577	0.25422
D2	0.2873	0.2813	0.2750	0.28122
AVERAGE	0.25711	0.25222	0.25222	0.25385

D X A	D o	D 1	D 2	AVERAGE
Ao	0.2007	0.2210	0.2753	0.23233
A1	0.2337	0.2727	0.2763	0.26089
A2	0.2440	0.2690	0.2920	0.26833
AVERAGE	0.22611	0.25422	0.28122	0.25385

A x T table S.S. = 3.495426 - 3.47980

= 0.015626

T x D table S.S. = 3.507856 - 3.47980

= 0.028056

D x A table S.S. = 3.524309 - 3.47980

= 0.044509

Main effects

S.S. for A	=	3.49280 - 3.4798
	=	0.0130022
S.S. for T	=	3.480088 - 3.4798
	=	0.000288
S.S. for D	=	3.50714 - 3.4798
	=	0.02734

Interaction S.S. for A x T	=	0.015626 - (0.000288 + 0.0130022)
	=	0.0023358
Interaction S.S. for T x D	=	0.028056 - (0.000288 + 0.02734)
	=	0.00428
Interaction S.S. for D x A	=	0.044509 - (0.0130022 + 0.02734)
	=	0.0041668

Three factor interaction A x T x D	=	0.04926 - (0.000288
		+ 0.0130022 + 0.02734
		+ 0.0023358 + 0.000428
		+ 0.0041668)
	=	0.0016992

Sum of 54 observations	=	13.708
Crude S.S. of 54 observations	=	3.533792
Correction	=	3.47980
Total S.S. about mean	=	0.053992

SOURCE OF VARIATION	SUM OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARE	VARIANCE RATIO	SIGNIFI - CANCE
MAIN EFFECTS					
A	0.013002	2	0.006501	37.149	* * *
T	0.000288	2	0.000144	0.823	N.S
D	0.027340	2	0.013670	78.114	* * *
TWO FACTOR INTERACTION					
A x T	0.002358	4	0.000584	3.337	* *
T x D	0.000428	4	0.000107	0.611	N.S
D x A	0.004167	4	0.001041	5.949	* * *
THREE FACTOR INTERACTION					
A x T x D	0.001699	8	0.000212	1.211	N.S
REMAINDER = ERROR	0.004732	27	0.000175		
TOTAL:-	0.053992	53			

N.S - NOT SIGNIFICANT
* - > 95%
** - > 97.5%
*** - > 99%

Frycap 7 - Holding Force

Sum of 27 observations	=	1719
Crude sum of squares	=	156344.5
Correction	=	109443
Total sum of squares about mean	=	46901.5

A X T	A 0	A 1	A 2	SUM
To	164.000	153.000	397.000	714.000
T1	98.000	222.500	227.500	548.000
T2	181.500	204.000	71.500	457.000
SUM	443.500	579.500	696.000	1719.000

T X D	T 0	T 1	T 2	SUM
Do	250.000	130.500	81.000	461.500
D1	164.000	198.500	160.000	522.500
D2	300.000	219.000	216.000	735.000
SUM	714.000	548.000	457.000	1719.000

D X A	D 0	D 1	D 2	SUM
Ao	102.500	156.000	185.000	443.500
A1	163.500	184.500	231.500	579.500
A2	195.500	182.000	318.500	696.000
SUM	461.500	522.500	735.000	1719.000

A X T	A o	A 1	A 2	AVERAGE
To	54.670	51.000	132.330	79.330
T1	32.670	74.170	75.830	60.890
T2	60.500	68.000	23.830	50.780
AVERAGE	49.280	64.390	77.330	63.667

T X D	T o	T 1	T 2	AVERAGE
Do	83.330	43.500	27.000	51.280
D1	54.670	66.170	53.330	58.060
D2	100.000	73.000	72.000	81.670
AVARAGE	79.330	60.890	50.780	63.667

D X A	D o	D 1	D 2	AVERAGE
Ao	34.170	52.000	61.670	49.280
A1	54.500	61.500	77.170	64.390
A2	65.170	60.670	106.170	77.330
AVERAGE	51.280	58.060	81.670	63.667

A x T table S.S. = 132817 - 109443

= 23374

T x D table S.S. = 120868.8333 - 109443

= 11425.8333

D x A table S.S. = 118739.50 - 109443

= 9296.50

Main effects

S.S. for A	=	112992.0555 - 109443
	=	3549.0555
S.S. for T	=	113216.5555 - 109443
	=	3773.5555
S.S. for D	=	114023.7222 - 109443
	=	4580.7222

Interaction S.S. for A x T	=	23374 - (3773.5555 + 3549.0555)
	=	16051.389
Interaction S.S. for T x D	=	11425.8333 - (3773.5555 + 4580.7222)
	=	3071.5556
Interaction S.S. for D x A	=	9296.50 - (3549.0555 + 4580.7222)
	=	1166.7223

Three factor interaction A x T x D = 46901.50 - (3549.0555
+ 3773.5555 + 4580.7222
+ 16051.389 + 3071.5556
+ 1166.7223)
= 14708.50

SOURCE OF VARIATION	SUM OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARE	VARIANCE RATIO	SIGNIFI - CANCE
MAIN EFFECTS					
A	3549.0555	2	1774.53	0.97	N.S
T	3773.5555	2	1886.78	1.03	N.S.
D	4580.7222	2	2290.36	1.25	N.S
TWO FACTOR INTERACTION					
A x T	16051.389	4	4012.85	2.18	N.S
T x D	3071.5556	4	767.89	0.42	N.S
D x A	1166.7223	4	291.68	0.16	N.S.
THREE FACTOR INTERACTION					
A x T x D	14708.50	8	1838.56		
TOTAL:-	46901.50	26			

N.S - NOT SIGNIFICANT
* - > 95%
** - > 97.5%
*** - > 99%